

## **Environmental Support to Space Launch**

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14. ABSTRACT We investigated environmental impacts to space launch at the Eastern and Western Ranges. In order to develop a truly responsive launch capability significant research needs to be conducted in specification and prediction of the atmosphere below 50,000 ft. Present research shows that weather is the leading cause of cancelled space launches (51% at Eastern Range and 58% at Western Range). The ability to forecast weather in support of current requirements was examined. Almost four years (2000 - 2004) of metric data was obtained from the Air Force Space Command (AFSPC). Metrics include weather warnings, weather advisories (watches) and forecasts of Launch Commit Criteria (LCC). The criteria were chosen based on the meteorological conditions found in the LCC. Results demonstrate current shortfalls in forecasting across several key environmental parameters which include lightning, convective and non-convective winds, precipitation and temperature. Both ranges show a large number of false alarms (forecasted but did not verify) for some of the environmental parameters. Even more significant are the low success scores or the probability of issued warnings meeting the desired lead time based on LCC. Ongoing research is focused on improvements in weather prediction which will lead to significant increases in operational responsiveness and decreased cost. Further research is required to improve weather forecasting so that responsive space launch will be realized.					
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## **1.. DECISION MAKERS' SUMMARY**

Space launch is, and will continue to be, sensitive to weather. In order to develop a truly responsive launch capability, significant research needs to be conducted in specification and prediction of the atmosphere below 50,000 ft. The Air Force Research Laboratory has a role to play in conducting militarily unique research into weather impacting space launch. The following list of military research requirements was developed by studying deltas between operational need and current capability. It is ordered by operational impact:

1. Improved methods of predicting lightning onset and cessation
2. Improved methods of predicting, characterizing, and tracking thunderstorms and associated hazards to include wind, hail, heavy rain and lightning
3. Improved methods of predicting and characterizing non-convective winds
4. Improved method of forecasting rainfall rates and amounts
5. Improved methods of forecasting temperatures

The overriding goal of these requirements is to support space launch operations. Failure to improve the ability to specify and forecast the state of the atmosphere will make it impossible to achieve current goals for responsive launch. Evaluation of forecast metrics and requirements documents indicates the following operational impacts of the current level of uncertainty in weather prediction:

1. Unnecessary launch delays and cancellations
2. Ground operations (including fueling, vehicle transfer, maintenance etc.) not being accomplished in a timely manner due to unneeded or excessively long weather warnings
3. Personnel being rendered unproductive due to restrictions associated with unneeded or excessively long weather warnings

As the Air Force's Research Laboratory, AFRL should help address military research requirements. We recommend that AFRL make a focused long-term commitment to conduct weather research in support of space launch. Such a program will require funding of approximately \$2M/yr to build core programs addressing the requirements outlined above. It would, by necessity, leverage research conducted by other government agencies and universities. The program could be augmented, as needed, by customer funding (when available) to address specific, shorter term issues.

It is envisioned that movement toward a truly responsive space force over the course of the next 20 years will require a greater understanding of the impact of weather on launch operations. Current shortfalls in the state of environmental prediction, despite the truly Herculean effort involved in supporting each and every launch, indicate weather will continue to impact operations well into the future. Efforts to produce an "all weather" Air Force have not been successful and there is no reason to believe an "all weather" Space Force will be developed in the foreseeable future. Research is required to improve weather forecasting or responsive space launch will not be realized.

## **2. INTRODUCTION**

This whitepaper seeks to determine the most effective way to utilize Air Force Research Laboratory (AFRL) resources to mitigate or exploit the environmental impact on space launch. It is the result of a cooperative effort between AFRL, Air Force Space Command (AFSPC), Space and Missile System Center (SMC), 45<sup>th</sup> Weather Squadron (45WS) at the Kennedy space Center, FL, and 30<sup>th</sup> Weather Squadron (30 WS) at Vandenberg AFB, CA.

Potential research projects were compiled by surveying current operational shortfalls. Potential research topics were reviewed to determine where (if anywhere) they are currently being explored. Relevant research already being conducted (at a sufficient level) by other government agencies, industry, or academia was identified and discussed. Space launch support shortfalls considered not satisfactorily addressed elsewhere were proposed for AFRL initiation. These potential projects were rank ordered based on operational impact.

We would like to thank all those that provided input for this paper, especially Mr. Donald Norquist (AFRL/VSBYA), Mr. Kevin Scro (SMC), Mr. Frank Guy (AFSPC), Mr. William Roeder (45<sup>th</sup> WS), Mr. John Madura (KSC), Mr. Johnny Weems (45<sup>th</sup> WS), Capt. Paul Lucyk (30<sup>th</sup> WS), and Mr. Leonard Wells (30<sup>th</sup> WS).

## **3. METHODOLOGY**

In order to determine research requirements, a survey of current launch requirements and capabilities at Kennedy Space Center/Cape Canaveral Air Force Station and Vandenberg Air Force Base was conducted. A list of deltas was formed outlining areas of potential improvement. The impact of unmet requirements was determined based on operational actions taken in response to weather events/forecasts. This list was used as a current research requirements baseline. Areas of maximum return were determined based on mission impact, current state of research (is anyone else doing it?), and AFRL current capability. Finally, a prioritized list of research requirements for AFRL consideration/action was developed along with the operational impact of conducting (or not conducting) the research.

### **3.1. Identification of Current Requirements**

Our effort to determine current requirements was based on a survey of space vehicle and launch site operational weather requirements. A list of space vehicles was made including the space shuttle and various rocket systems. Air breathing systems (including the ER-2, various NASA chase planes and shuttle transport vehicles) were excluded to allow us to concentrate on space launch requirements. Launch commit criteria, site weather watch, and weather warning criteria were collected as was historical weather based launch delay data. Each of the weather criteria was evaluated for operational impact. Often several impacts or operational actions were listed for a single warning/notification. For example, multiple events occur when lightning is

observed within 5 miles of Kennedy Space Center (KSC). These actions range from ceasing fueling of space vehicles to sheltering workers at exposed areas.

Multiple groups coordinate on weather support to a successful space mission. For the purpose of this paper we concentrated on launch support activities at Kennedy Space Center and Vandenberg AFB (VAFB). This is not to imply that there are not significant environmental impacts at other sites or on the non-launch (/recovery) portions of a mission. Current launch support involves local support provided by 45<sup>th</sup> Weather Squadron, 30<sup>th</sup> Weather Squadron and strategic center support provided by Air Force Weather Agency (AFWA), Fleet Numerical Meteorological and Oceanographic Center (FNMOC), and various US Government weather agencies. Both weather squadrons have a variety of special equipment to help them observe and forecast weather for a space launch. More information on the current weather support structure and available equipment is found in Appendix A.

### **3.2. Current Capability Determination and Shortfall Identification**

In order to determine current environmental support capability Air Force Space Command (AFSPC) metrics were analyzed. These metrics include numbers of issued and required weather notifications stratified by lead time. An analysis of current capability based on these metrics is provided.

Based on our analysis of launch site metrics a list of current capability shortfalls was determined. This list was then rank ordered by impact to mission success and analyzed to determine if the shortfall was due to the state of atmospheric science or rather the result of other factors (comm., limits, organizational structure, resources etc.) Shortfalls caused by the current state of atmospheric science were then listed by meteorological area (severe weather, non-convective winds, etc.) and rank ordered by impact. This final list of research areas in which the state of science is causing us to be unable to meet mission requirements formed our current support deficit baseline. It is this list of research areas that will have the greatest impact on our current ability to perform the space launch mission.

### **3.3. Identification of Areas of Maximum Return**

The list of requirements was next evaluated to determine which research areas were best addressed by AFRL. If a sufficient research effort was already being conducted by another agency (NASA, other government, university, or industry) it was not included in the list for AFRL consideration. The final list of proposed research consists of high impact projects, which are not being sufficiently pursued by others, and have a high likelihood of success.

## **4. WEATHER IMPACTS TO SPACE LAUNCH OPERATIONS/CURRENT REQUIREMENTS**

#### 4.1. Launch Commit Criteria

Weather significantly impacts launch operations. In fact weather is the single largest factor in launches being canceled (Fig. 1). An extensive set of launch commit criteria is included as Appendix B. The total number of events that occurred at each range using the LCC is found in Appendix 3. In many cases the presence of adverse weather in the local area is sufficient to delay or cancel a launch.

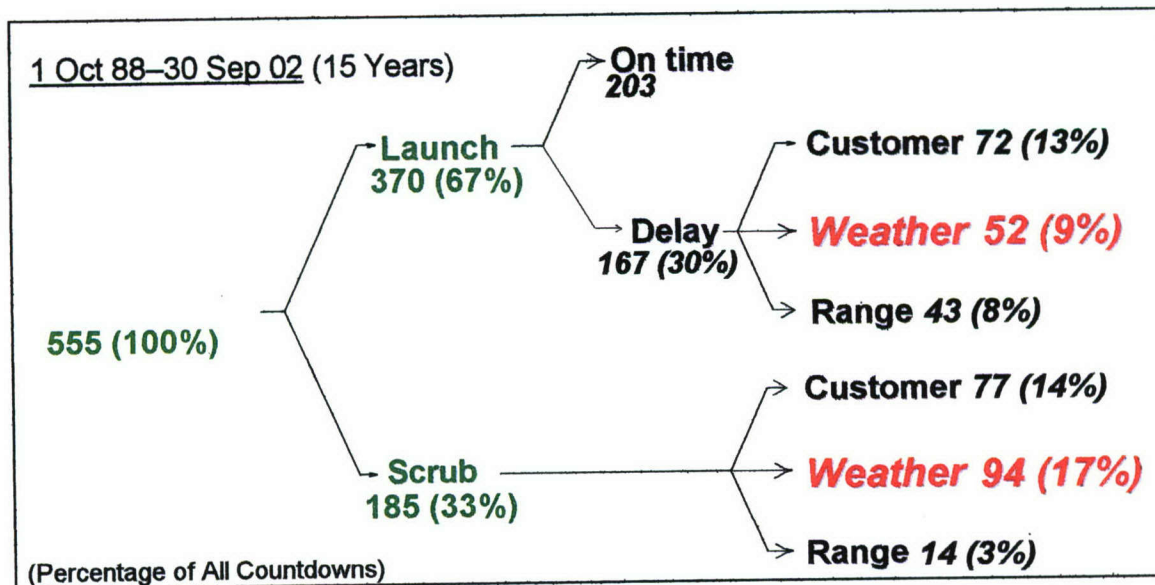


Figure 1. Launch delays and scrubs by cause Oct 88 – Sep 02 (from 45 WS).

Lightning is the most frequent factor in weather launch delays at the CCAFS/KSC. Launches can be delayed or canceled due to the presence of lightning in the immediate area, or along the planned flight path of the space vehicle. Launches may also be impacted by conditions associated with rocket-induced lightning. In these cases, the atmosphere is sufficiently charged that the exhaust plume forms an electrical path and induces a lightning event. Several of the launch commit criteria are designed to forecast conditions favorable for rocket-induced lightning. For example launches are not allowed for Atlas and Delta rockets when the flight path is through a non-transparent detached thunderstorm anvil (within 3 hours of the last lightning event). Additional restrictions are in place for flights of space vehicles through or near clouds of various heights and temperatures. Electric field mills are used to measure potential through the atmosphere and Space Shuttle launches can be canceled if readings exceed 1 kV/m. A list of research requirements for CCAFS/KSC is found in Appendix D.

Winds are another factor in delaying/canceling launches. At the VAFB, winds are the greatest concern for scrubs (Fig. 2). Both high winds (surface and along the flight path) and unforecasted winds can impact a launch. High winds are hazardous due to their ability to damage vehicles and infrastructure as well as the possibility of throwing a vehicle into its own launch platform. Unforecasted winds can cause delays due to the need to reset navigation systems. Winds are also used to predict debris paths in the

event of a catastrophic mishap. Launches can be delayed/canceled if predicted winds have a debris path that overlies populated areas.

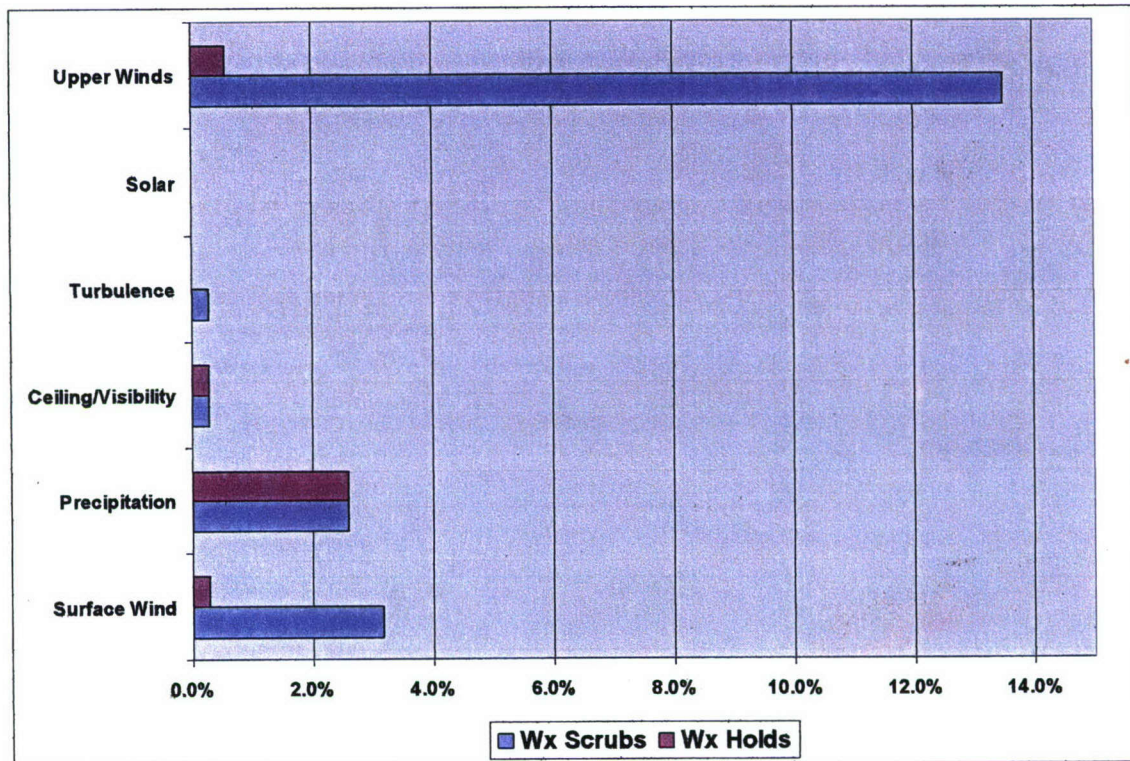


Figure 2. Weather Scrubs and Holds at Vandenberg AFB from February 88 – May 03. Hold is defined as an interruption in countdown due to adverse conditions.

Visibility is required for space shuttle launches and the launch may be canceled if portions of the flight path are forecast to be obscured by clouds. Various space vehicles also have temperature thresholds and launches will be impacted by out of range temperatures. The Atlas 2A, for example, will not launch if temperatures are forecast to be below 40F.

One aspect of the LCC that is not discussed in depth in this paper is Lightning Launch Commit Criteria (LLCC). The LLCC is a subset of weather rules to avoid natural or triggered lightning during space launch and is the same for all USAF and NASA launches. This paper focuses on the LCC which involves overall thunderstorms and severe events but does go into the detail of the equipment and sensors that measure electrical fields directly. There is a need to analyze the sensitivity of the LLCC in launches dependent on vehicle configuration and the climatology for mission planning days before liftoff.

Launch commit decisions are made after considering many inputs (all of which can be overridden in the interest of safety). Nonetheless, the ability to accurately predict the weather is a key factor in timely space launch.

## **4.2. Ground Operations**

Weather is also a major factor in the ability to conduct ground operations at launch facilities. RTOMI S0018.100 (Adverse Environmental and Lightning Monitoring at LC 39) outlines specific actions taken by the Space Shuttle program in response to weather forecasts and observations. Each of the weather advisories and warnings issued at CCAFS/KSC sets into motion activities designed to minimize mission degradation/delay, space vehicle/support structure damage, and loss of life. Similar actions are taken in support of expendable launch vehicles. The complete RTOMI S0018.100 (345 pgs) is included (on disk) as Appendix E. This section summarizes some of the actions taken in response to weather advisories and warnings to give the reader a feel for the magnitude of weather's impact on space launch operations. These actions are separate from the Launch Commit Criteria (contained in Appendix B) which are used to determine when it is safe to launch a space vehicle.

### **4.2.1. What happens when lightning is forecast/observed?**

Lightning is the most challenging of weather advisories/warnings due to its frequency of occurrence and its impact to operations. Actions in response to lightning fall into 3 categories: Actions taken in response to a weather advisory (lightning forecast to occur within 30 minutes within 5 miles of the facility); actions taken in response to a lightning warning; and actions taken in response to a lightning strike.

When a lightning advisory is issued launch support is impacted in a variety of ways. Cameras are activated to record any potential damage to launch facilities. Fueling and transfer of combustible liquid operations are delayed if not already in progress. This includes fueling of space vehicles, purging of fuel from space vehicles and the transfer of combustible liquids to and from the vehicle and various storage facilities. If fueling operations are in progress, actions are taken to ensure work can be terminated if lightning is observed. Hoisting operations may only begin and continue if confined to a lightning protected building (additional restrictions are in place for hoisting of flammable/combustible liquids). Movement of space vehicles in various configurations are delayed as is movement of payloads (when they contain hazardous materials). Connections between the vehicles and platforms may be delayed and support facilities begin closure of outside doors.

When a lightning warning is issued still more procedures are enacted. Most actions involving the use of combustible or flammable materials are discontinued. Personnel are generally asked to proceed to a lightning protected facility. Certain areas in and around the launch facility are closed. Additional restrictions are placed on the movement of equipment and space vehicles. Payload canisters containing hazardous material are moved to a lightning protected facility (or stopped in place and personnel are evacuated). Work across several space vehicle/ground facility interfaces is prohibited.

When lightning is observed to have struck a vehicle, launch infrastructure, or facility, data is gathered (to include camera data) confirming the strike. A Lightning Committee is alerted and a rigorous set of procedures are enacted to determine the extent of damage to facilities, vehicles and payloads.

#### **4.2.2. What actions are taken in response to tornado watches/warnings?**

Tornado watches and warnings are handled similar to USAF bases with personnel being ready to shelter during a watch and mandatory sheltering being implemented when a tornado is sighted. Kennedy Space Center has the capability to track waterspout and funnel cloud movement using its camera systems. Perhaps the greatest difference between CCAFS/KSC and other locations is the presence of national assets and the potential for property damage in the billions of dollars.

#### **4.2.3. What happens when heavy rain is forecast/observed?**

Actions in response to heavy rain warnings consist mostly of controlling water intrusion. As such, payloads are sheltered, doors are closed, hatches are closed, and seams are taped as appropriate. Vent doors are set to proper purge positions to ensure water doesn't enter tanks. Reconfiguring vehicles following a heavy rain event is an involved procedure safely undoing all actions taken above while guarding against possible chemical contamination (from payloads), cleaning off seals, and inspecting for water damage.

#### **4.2.4. What happens when high winds are forecast/observed?**

Weather warnings are issued for a variety of forecast wind speeds. In general, the higher the predicted speed, the more restrictions are placed on operations and more effort needs to be expended in securing equipment. Below is a sample of actions taken in response to wind warnings. A complete list can be found in Appendix E.

When sustained wind speeds are predicted to exceed 30 kts, no work is permitted on facility roofs, structure tops and unprotected areas. Movement of space vehicles between facilities and some tanking operations are restricted. When winds top 40 kts, most equipment movement is restricted and when winds exceed 45 kts, all but emergency/security operations are halted.

In addition to halting operations, numerous steps are taken to secure equipment against potential wind related damage. Such measures include: activating sensors and cameras to measure wind stress related damage, securing structures and vehicles, installing doors and panels, sheltering equipment, monitoring vent seals for leakage. At very high wind speeds liquid oxygen and liquid hydrogen tanks are pressurized to prevent damage.

It should be noted that procedures call for accomplishing only actions that can be safely done in the time allotted. If a warning is issued with insufficient lead time then

actions will be left unfinished in order to properly protect the workforce. A detailed set of procedures is followed after any high wind events to assess damage to launch vehicles, equipment, and infrastructure.

#### **4.2.5. What happens when low temperatures are forecast?**

Actions in response to low temperature warnings consist mostly of powering up various heating systems to ensure various space vehicle components and chemicals (to include water) don't freeze.

#### **4.2.6. Summary**

Weather is the leading cause of canceled or delayed space launches. The launch commit criteria of space vehicles are significantly more complex and involved than similar criteria for air vehicles. Ground operations at space launch facilities are also significantly more weather sensitive than ground operations at airports. Due to these weather sensitivities, space launch has greater forecast accuracy requirements than air launch.

### **5. CURRENT FORECASTING CAPABILITY AND SHORTFALLS**

The ability to forecast weather in support of current requirements was examined utilizing almost 4 years of data. Analysis of this data did not detect any shortfalls in forecast discipline (missed warnings) but did show several areas where the current state of the science falls short of requirements. Incidentally, if a forecast was "missed", it was labeled as negative lead time. Notably, the ability to determine the onset and cessation of weather associated with convection (lightning, hail, winds) needs improvement.

#### **5.1. Description of Data-Metrics**

Almost four years (2000 – 2004) of metric data was obtained from the Air Force Space Command (AFSPC) for two separate sites, CCAFS/KSC (Eastern Range) and Vandenberg AFB (Western Range). Metrics include weather warnings, weather advisories (watches) and forecasts of Launch Commit Criteria (LCC). The Eastern Range site includes Cape Canaveral Air Force Station (CCAFS), Patrick AFB, Melbourne Stations, and Kennedy Space Center (KSC). The Western Range site is Vandenberg AFB. Over the last three and a half years these criteria have evolved. For the purposes of this paper we analyzed only data that was available for the entire period of record. Tables 1 and 2 show the criteria that were chosen for the Eastern and Western Range, respectively. Each event has a minimum and maximum value and a desired lead-time associated with it. Lead time is defined as the duration of time before the event actually occurs. The metric data obtained are number of forecast and observed occurrences of each event reported in eight categories. These categories included required (an observed occurrence) and issued (a forecasted occurrence). The issued category is further broken down into three subcategories: met desired lead time

(DLT), did not meet required time and false alarms (issued not required). The DLT not met subcategory is further stratified by negative or zero lead time, met DLT 1-49% (first half of the time period), and met DLT 50-99% (last half of the lead time period). One category, required not issued, was not included in this study as there were no occurrences.

Event	Min Criteria	Max Criteria	Desired Lead Time (Minutes)
Tornado/Waterspout	0	999	5
Fair Weather Waterspout Advisory (Miles from Site)	0	5	5
Winds GTE 60 Knots (Convective)	60	999	60
Winds 50 - 59 Knots (Convective)	50	59	60
Winds GTE 50 Knots (Convective)	50	999	60
Winds 35 - 49 Knots (Convective)	35	49	30
Winds 25 - 34 Knots (Convective)	25	34	30
Winds GTE 60 Knots (Non-Convective)	60	999	60
Winds 50 - 59 Knots (Non-Convective)	50	59	60
Winds GTE 50 Knots (Non-Convective)	50	999	60
Winds 35 - 49 Knots (Non-Convective)	35	49	30
Winds 25 - 34 Knots (Non-Convective)	25	34	30
Hail (Any Size)	0	999	60
Heavy Rain (GTE 2 inches in 12 hours)	2	999	5
Rain Advisory (GTE 1 inch)	1	999	30
Lightning Within 5 Miles of Site	0	5	30
Freezing Precipitation Advisory	0	999	30
Temperature 32 - 39 F Advisory	32	39	240
Temperature 25 - 31 F Advisory	25	31	960

Table 1. Launch Commit Criteria for selected AFSPC sites for the Eastern Range.

Event	Min criteria	Max criteria	Desired lead time (minutes)
Tornado/Waterspout	0	999	>=5
Winds 35-49 Knots (Non-Convective)	35	49	>=60
Winds 50-64 Knots (Non-Convective)	50	64	>=120
Winds GTE 65 Knots (Non-Convective)	65	999	>=120
Winds 35-49 Knots (Convective)	35	49	>=60
LTG	0	5	>=30
Hail Any Size	0	999	>=60
Heavy rain ( $\geq$ 2 inches in 12 hours)	2	999	>=60

Table 2. Launch Commit Criteria for Vandenberg AFB or Western Range.

In order to analyze forecast capability, contingency tables (shown in Table 3) were constructed. If an event was forecasted with desired lead time and observed, it was placed in the top left box (Hit). If an event was forecast but did not occur, it was a false alarm and was placed in the bottom left box (False Alarm). If an event was not forecast with the desired lead-time, it was considered a missed forecast (Miss).

		Forecast	
		Y	N
Observed	Y	Hit	Miss
	N	False Alarms	

**Hit = Met DLT**  
**Miss=DLT not met**

Table 3. Contingency Table. Hit: Forecast yes, observed yes; Miss: Forecast no, observed yes; False Alarms: Forecast yes, observed no.

Statistical measures of accuracy were computed as derived using the formulas in Table 4. The Hit Rate (HR) [or commonly known as Probability of Detection (POD)] represents that fraction of observed "yes" events were correctly forecast. For this study, this is defined as the probability of issued warnings that met the desired lead-time but ignores false alarms. A perfect hit rate calculation would produce a value of 1.00. It is noted that HR is sensitive the climatological frequency of an event. This is useful for analyzing rare events. The False Alarm Ratio (FAR) is the fraction of predicted "yes" events that did not actually occur. This is similar to the HR except it compares the false alarms to the total number of hits and false alarms. The FAR ranges from 0 to 1 (0 being a perfect score). The FAR is sensitive to false alarms but ignores misses (DLT not met). It is also very sensitive to the climatological frequency of an event and should be used in conjunction with the HR.

The last statistical formula is the Success Score (SS) also known as Critical Success Index (CSI). The SS measures the fraction of events that were correctly predicted. It can be thought of as the accuracy of correctly forecasted events. SS is only concerned with forecasts that count. This score is very sensitive to required forecasts; it penalizes both misses and false alarms. It does not distinguish the source of a forecast error. In relation to this study, this score is the fraction of all issued warnings(including false alarms) that met the desired lead-time. The range for SS is 0-1 with 0 pertaining to no skill.

Formula definition	Range
Hit Rate = hits/(hits+misses)	0-1. Perfect score 1
False Alarm Ratio = FA/(FA+hits)	0-1. Perfect score 0
Success Score= hits/(hits+misses+FA)	0-1. Perfect score 1

Table 4. Formula definition and statistics table for Hit Rate, False Alarm Ratio and Success Score.

The statistics were broken up by meteorological type including severe events, precipitation, convective winds, non-convective winds and temperature. If an event does not have a value associated with it, then there were no occurrences or forecasts during that season. If the HR and SS is zero and the FAR is one, then there were forecasts issued but no observances (i.e., false alarms only). If the HR and SS is zero

and the FAR is blank, then there were occurrences but no forecasts that met DLT (i.e. misses only).

## 5.2. Analysis of Eastern Range

Statistical measures of accuracy for the Eastern Range are shown in Table 5. This analysis is calculated based on all four years of data selected and broken down by meteorological event type.

### 5.2.1. Severe Events

In general, severe events are seasonally driven with the summer and fall having the greatest number of occurrences. These events are associated with cumulonimbus clouds. The weather systems that spawn them can range from a single cell thunderstorm producing strong winds to severe thunderstorms called supercells. Supercells are large thunderstorms with deep rotating updrafts that can have a lifespan of several hours. They can produce lightning, hail, damaging winds and tornadoes.

Such systems tend to develop in the afternoon and early evening when the effects of the sun are greatest. All thunderstorms have the potential to disrupt operations.

Criteria	Hit Rate Probability of Issued Warning meeting desired lead time (ignoring FA)	False Alarm Ratio	Success Score Probability of Issued warning meeting desired lead time (including FA)	Number of observed Occurrences
<b>Severe events</b>				
Tornado/Waterspout	0.71	0.72	0.25	7
F W Waterspout(Adv)	0.00	1.00	0.00	4
LTG	0.68	0.49	0.41	3855
Hail Any Size	0.43	0.89	0.09	21
<b>Precipitation</b>				
Heavy rain (> 2 in/12 h)	1.00	0.60	0.40	8
Rain >=1 Inch (Adv)	0.69	0.57	0.36	32
Freezing Precip (Adv)				0
<b>Winds Convective</b>				
Winds GTE 60 (Conv)		1.00	0.00	0
Winds 50-59 (Conv)	0.30	0.90	0.08	20
Winds GTE 50 (Conv)	0.30	0.92	0.07	27
Winds 35-49 (Conv)	0.75	0.66	0.31	331
Winds 25-34(Conv Ad)	0.67	0.62	0.32	152
<b>Winds Non-Convective</b>				
Winds GTE 60(NonConv)		1.00	0.00	0
Winds 50-59(NonConv)		1.00	0.00	0
Winds GTE 50(NonConv)	0.00	1.00	0.00	2
Winds 35-49(NonConv)	0.71	0.44	0.46	75
Winds 25-34(NonConvAd)	0.79	0.51	0.43	160
Steady Wind >=22 (Adv)	0.62	0.48	0.40	37
<b>Temperature</b>				
Temp 32-39F (Adv)	0.62	0.40	0.44	53
Temp 25-31F (Adv)	0.42	0.67	0.23	26
Temp <=24F (Adv)		1.00	0.00	0

\* empty columns due to 0 in denominator

Table 5. Statistical results for Hit Rate (HR), False Alarm Ratio (FAR) and Success Score (SS) for Eastern Range

Unfortunately the data is unable to support analysis of the impact of warnings issued for an excessive period of time. We hypothesize that forecasting cessation of conditions associated with severe weather events is as challenging as forecasting the onset of such conditions.

Our analysis of current capability to predict severe weather events in support of space launch is as follows:

1. Lightning is the most frequent event to impact operations. There is considerable room for improvement in forecasting the conditions necessary/sufficient for lightning. Lightning forecasts have a 68% probability of meeting desired lead-times. For all lightning forecasts issued, almost half (49%) are false alarms. The number of successful forecasts averages around 41%.
2. Hail events were poorly predicted with 43% of all forecasts meeting the desired lead-time. False alarm rates were extremely high with 89% of all forecasts not verifying. This is shown in the low number of successful forecasts found to be 9%. Hail events, although not as common as lightning, are forecast poorly and have an unusually high false alarm rate and have the one of the lowest success values for the entire study.
3. The capability to predict severe weather needs improvement to meet current requirements. The data show a lack of confidence in the current state of forecasting as evidenced by high false alarm rates and low success scores.

### **5.2.2. Precipitation**

Precipitation events occur year round. There are three types of events listed as LCC: heavy rain which is defined as greater than 2 inches in 12 h, a rain advisory that is greater than 1 inch, and freezing precipitation. For this time period, there are 8 heavy rain events, 32 rain events ( $\geq 1$  inch) and no freezing rain events.

Our analysis of current capability to forecast precipitation in support of space launch is as follows:

1. Although all heavy rain events were forecast, 60% of those forecasted were false alarms. The success rate or the probability of issued warnings meeting the desired lead-time was only 40%.
2. Rain events occurred three times more often than heavy rain events. The results were very similar to those of heavy rain events with the exception of the hit rate. The hit rate for rain events was only 69% compared to 100% of heavy rain. False alarms occurred 57% and the success rate was 36%.
3. There is significant room for improvement in the forecasting of rain rates/amounts in support of space launch.

### **5.2.3. Convective Winds**

Next to lightning, convective winds are the most frequent events. These winds are associated with the same strong convective systems as severe events. There are five convective wind categories, ranging from a convective advisory for 25-34 kt winds up to a warning for winds greater than 60 kts.

Our analysis of current capability to forecast convective winds in support of space launch is as follows:

1. The SS is very low for all convective wind types. The highest probability of an issued warning being successfully forecast is 31% for winds 35-49 kts and 32% for winds 25-49 kts. As the winds become stronger, (GTE 50 kts), the success rates drop dramatically to the single digits (7% and 8%)
2. The false alarm rate for convective winds overall is higher than for any other meteorological event. Winds GTE 50 kts are almost always forecasted incorrectly with a false alarm rate of 92%. There is a need to improve forecasting of convective winds.

### **5.2.4. Non-Convective Winds**

Non-convective winds are not forecasted as frequently as convective winds. While convective winds are usually associated with larger mesoscale systems, non-convective winds are connected to larger, synoptic scale events such as a frontal passage. The non-convective winds are broken into the same categories as convective winds with the addition of an advisory for steady winds greater than 22 kts. Winds 25-34 kts had the most events at 160, winds 35-49 kts occurred 75 times and steady winds 37 times. Winds greater than 50 kts only occurred twice.

Our analysis of current capability to forecast non-convective winds in support of space launch is as follows:

1. The HRs for non-convective winds were one of the highest of any events in the dataset with winds 25-34 kts at 79% and winds 35-49 kts at 71%. The FAR ranged from 44% to 51% for winds less than 50 kts.
2. The success rates for non-convective winds range from 40% for steady winds GTE 22 kts to 46% for winds 35-49 kts. Although non-convective winds are better forecasted than convective wind events, there is still room for improvement with almost half of all forecasts being false alarms.

### **5.2.5. Temperature**

The last group of weather criteria is cold temperature advisories. There are three cold weather advisories: less than 24°F, 25-31°F and 32-39°F. There were 0, 26 and 53 occurrences respectively. Since these advisories would be confined mainly to the cooler seasons, there is no data for the summer or fall.

Our analysis of current capability to forecast temperature thresholds in support of space launch is as follows:

1. The HR was 42% for temperatures ranging from 25-31F and 62% for temperatures ranging from 32-39F.
2. There is room for improvement in the forecasting of temperatures in support of space launch.

Due to the large amount of meteorological events at the Eastern Range, a seasonal statistical study was performed and can be found at the end of this paper in Appendix F.

#### **5.2.6. Summary**

Overall, the HR was dependent on the event type and the False Alarm Rates for all events were high. This indicates that the forecasters are forecasting events that do not verify (overforecasting). The majority of the events had a low SS. SS includes false alarms in its calculation and can be reduced by any tendency to overforecast.

It is significant that false alarm rates are high in almost all categories of weather event. This indicates that the state of forecasting is not sufficiently advanced to meet current space launch requirements. Analysis of almost four years of data shows that significant shortfalls exist in our current ability to forecast the following events to the level of specificity required by space launch:

1. Lightning Onset and Cessation
2. Thunderstorms and Associated Hazards (including winds, hail, lightning)
3. Non-Convective Winds
4. Rainfall Rates and Amounts
5. Temperature Thresholds

#### **5.2.7. Actual Lead Times for Eastern Range**

To determine the frequency that a forecast or weather advisory was successfully issued within the desired lead time, actual forecasted lead times for meteorological events were analyzed. These statistics only include the forecasts issued for observed events, and not the false alarms. Starting in May 2002, the Eastern and Western Ranges began tracking the lead times for many of their meteorological events. These events include convective winds (GTE 50 kt, 50-59 kt, 35-49 kt, 25-34 kt advisory), non-convective winds (35-49 kt, 25-34 kt advisory), steady winds advisory ( $\geq 22$  kt), lightning, rain advisory ( $>1$  inch), heavy rain (GTE 2 in/12 h) and temperature advisory (25-31F, 32-39F, 33-40F). Histograms were created in 30 minute increments. Each increment contains 29 minutes below and including the column value on the x-axis. For example, if there are 10 values in the column for 59 minutes, this means that these 10 values range from 30 and 59 minutes. All values in the 0 column shows all negative lead times.

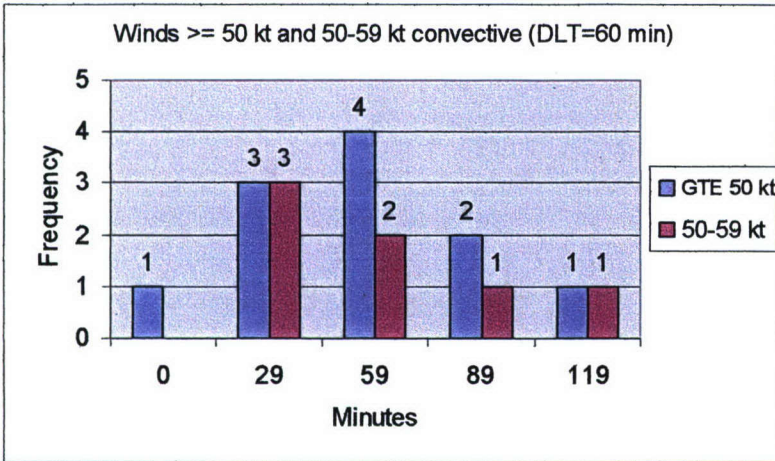


Figure 3. Actual Lead times of forecasted convective winds GTE 50 kt and 50-59 kts for Eastern Range.

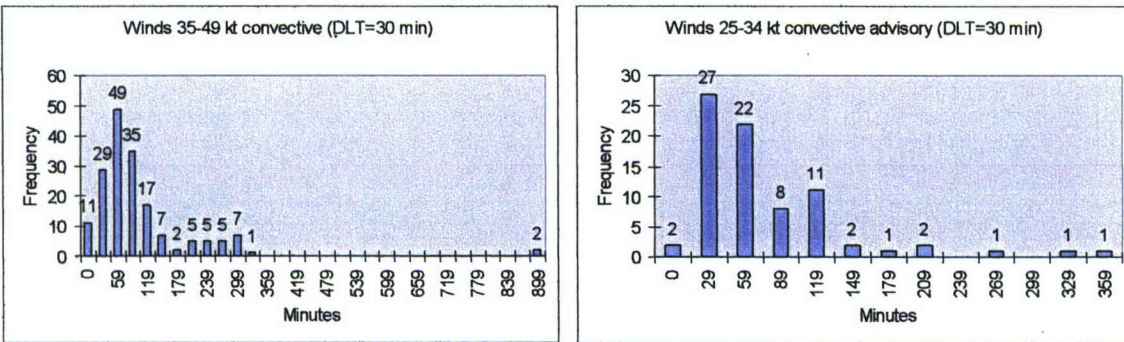


Figure 4. Actual lead times for convective winds for Eastern Range

Figure 3 shows the lead times for winds GTE 50 kt and 50-59 kt convective winds. A large number of the warnings (73%, 71%) were issued much later than the desired lead time (60 minutes). Convective winds from 25-35 kt advisory and 35-49 kt shown in Figure 4 have a better response time with lead time failures of 37% and 23% respectively. As for non-convective winds from 35-49 kt, these results, shown in Figure 5, were very similar to convective winds with 33% and 14% for 25-34 kt advisory of all forecasts failing to meet required time. The last wind category, steady winds greater than 22 kts, had a 42% failure rate (not shown).

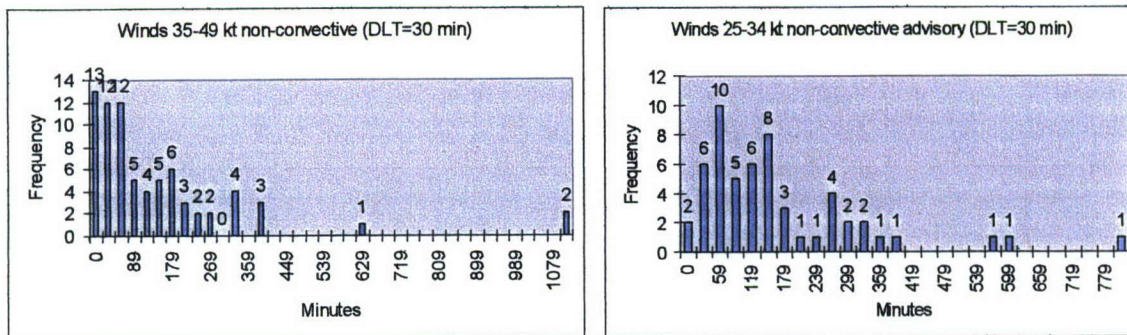


Figure 5. Actual lead times of forecasted non-convective winds for Eastern Range.

The most prominent meteorological event that occurs at the Eastern Range is lightning. The desired lead time to forecast lightning events is 30 minutes. Figure 6 shows the total lead times for all lightning events (29% of all forecasts of events that occurred failing to meet the required lead time) and all temperature events. All of the latter events occurred in the winter. For temperatures between 32-39F and 33-40F, the desired lead time was 240 minutes with lead times of 29% and 70% failing to meet the required times. Temperatures between 25-31F with desired lead time of 960 minutes had a failure of 90%. It suggests that the forecasters have a lot of difficulty forecasting temperature below the freezing point, especially since there is a significantly large (240 or 960 minute) lead time.

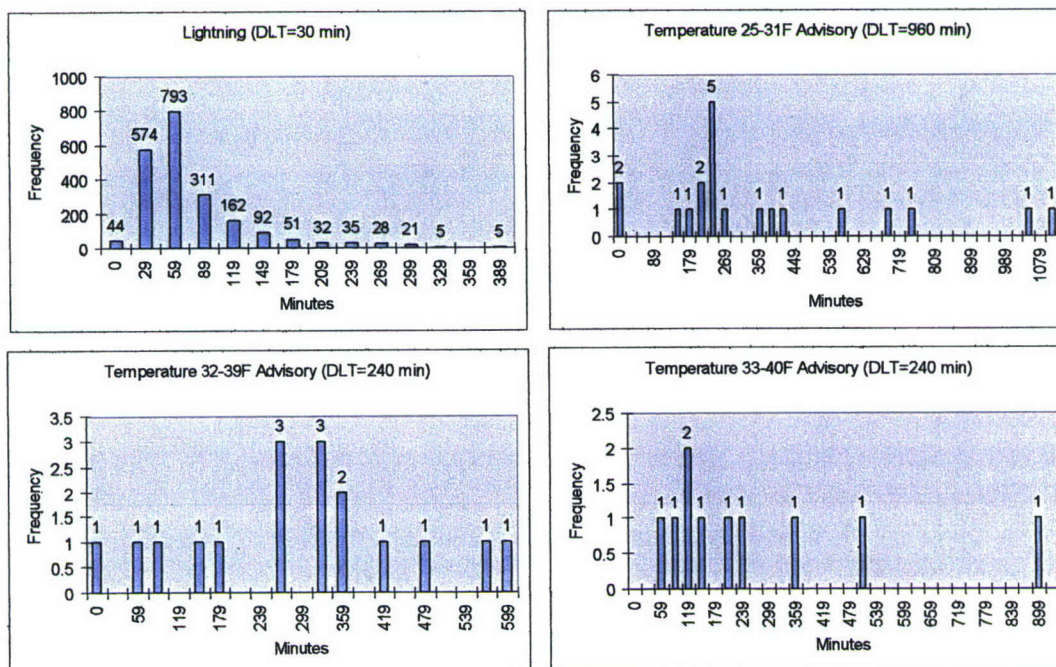


Figure 6. Lightning and temperature advisory forecast lead times for Eastern Range.

It is observed that a pattern among certain meteorological events has emerged in the histograms. Some show a distinct pattern of larger amounts of lead times within 90 minutes of the event. Others, where no such grouping exists, have lead times that seem scattered or uncorrelated. For example, convective winds/advisories for spring, summer and fall all have a noticeable spike in forecast lead times 60 and 120 minutes. For non-convective winds/advisories, there does not seem to be a pattern or a distinctive spike. Since convective activity in Florida can develop very rapidly with minimal notice, there is less lead time available to predict the threat to the launch site. Non-convective winds, whether they develop from sea breeze events or within a larger synoptic scale pattern usually have longer warning times associated with them.

#### **5.2.8. Summary**

There are a significant number of actual warnings/advisories that are issued too late to meet the desired lead time for many meteorological events. These results reinforce the difficulty of forecasting certain events and issuing of warnings within a desired time range. We speculate that the large number of actual warnings/advisories that failed to meet the DLT would decrease with improved forecast guidance. These shortfalls suggest that the more research is needed to meet these requirements:

1. Convective winds/advisories
2. Temperature advisories
3. Lightning
4. Non-Convective Winds

### 5.2.9. Overall Cost of Ground Operation Support During Lightning Advisories

In 1992, KSC collected one year of data containing information on the cost of ground operational support of space shuttles during lightning advisories within 25 nm of the launch site. The data collected included number of hours that the lightning advisories were valid, number of people affected, and contractor rate per hour. Overall there were 1307 hours of lightning advisories that were required. During the year, there were 775 people that work the ground operations that were affected by lightning sensitive work at KSC over three daily shifts shown in Figure 7. This number had dropped considerably from years past due to the implementation of updated lightning advisories that allow certain ground operations to continue for longer periods before being halted. Lightning advisories affected an average of 400 of these workers. In 1992, the average cost for a contract employee was \$46/hour.

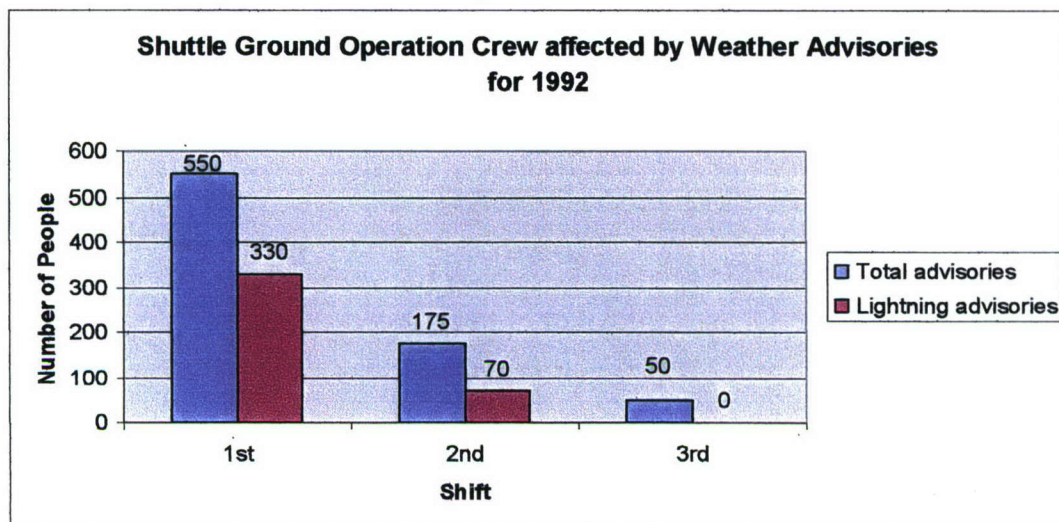


Figure 7. Shuttle Ground Operation Crew affected by Weather Advisories (1992).

Therefore, the cost of ground crew operations during a lightning advisory would equal multiplying the number of hours advisory is valid, the number of people affected and the hourly wage. The cost for the ground operation crew that halted during lightning advisories that verified in 1992 is \$24.1M. This does not take into effect any other type of weather warnings or advisories or other launches that occur at KSC.

Annually, there are a couple of thousand cloud-to-ground lightning strikes per year that occur within 5 nm of KSC. For our dataset, there were four full years of data, 2000-2003 (2004 only until June). The total number of required and issued lightning advisories is shown in Figure 8. The average annual number of required lightning advisories that verified in these four years was 855. The average annual number of issued lightning advisories was 1429. Therefore the difference or the average number of lightning advisories that were unnecessarily issued annually was 574 (or 40%). If we

calculate the cost of ground operations for these 574 advisories and assume that these advisory were only issued for one hour, since contract employees are charged at an hourly rate, it would cost at the very minimum a yearly average of \$10.5M. In other words, this value represents the average number of yearly lightning forecasts (574) that were issued unnecessarily, with each advisory only issued for one hour for shuttle ground operations and assuming that only 400 employees were affected and the hourly rate of \$46 (FY92 dollars). Presently, it is assumed that more employees would be affected and the hourly rate has risen in the last 14 years. Also, this is greatly underestimating the cost due to the LLCC rule which states that launching cannot occur 30 minutes after a lightning strike has occurred within 10 nm of the launch pad and the lead time for forecasting lightning over this area is 30 minutes which would affect certain ground operations. Therefore, it is reasonable to assume that a minimum time that a lightning advisory is issued is for 2 hours or at an annual cost of \$21M. There is no actual data on the average number of hours a lightning advisory is issued for.

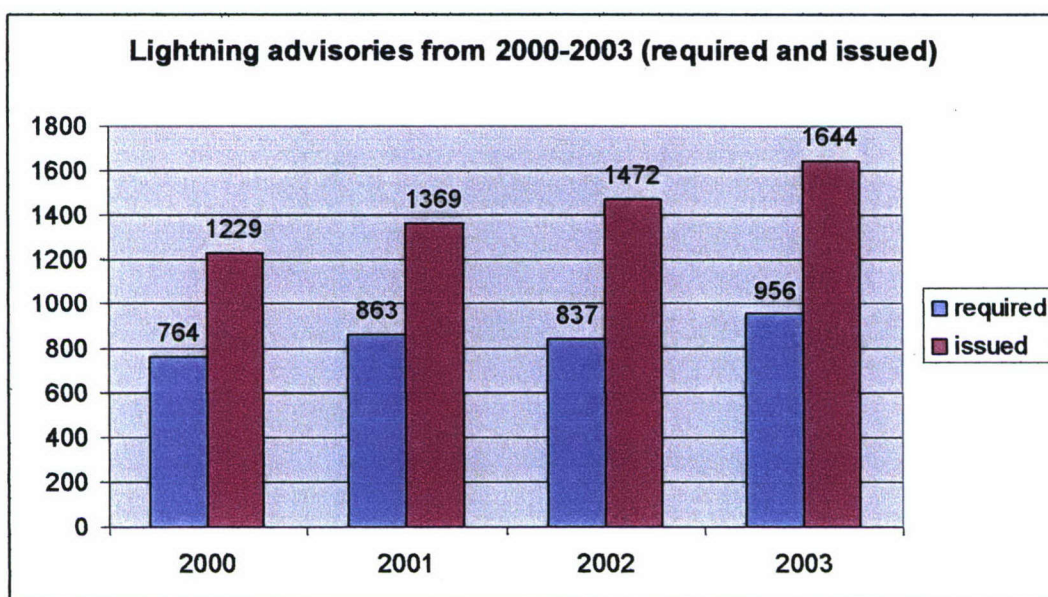


Figure 8. Lightning Advisories from 2000-2003 for required and issued forecasts.

This cost is for 40% of all lightning forecasts which are issued but not required. If further research on the development and cessation of thunderstorms was performed, a 25% improvement in forecasting would save a minimum of \$5.25M annually (if each individual lightning advisory throughout the year had a minimum delay of 2 hours).

### 5.3. Analysis of Western Range

For Vandenberg AFB, site of the Western Range for space launch, there were only eight LCC that were utilized based on atmospheric conditions affecting the launch site. Unlike the Eastern Range, Vandenberg AFB's major environmental impact is lack of visibility due to its location in the coastal region of southern California. The maritime

climate usually prevails within the basin causing a persistent temperature inversion layer. This causes fog, haze and smog, all of which are common within the area. Climatologically, during the summer, a high pressure zone generally limits the amount of precipitation. The location of the launch sites allows it to become heavily affected by the maritime westerly flow off of the Pacific Ocean and heavily influenced by strong easterly winds that develop from mountain ranges to the east. In the LCC there is only one criterion for limited visibility (Visibility < .5 mi). Unfortunately there is no data available for this parameter which has such a great influence over the launch area.

Table 2 shows the eight launch criteria that were chosen for this particular site. These eight LCC were consistent throughout the four-year study. These include Tornado/Waterspout, non-convective winds 35-49 kt, 50-64 kt and greater than 65kts, convective winds 35-49 kt, lightning, hail and heavy rain. The analysis methodology applied to Vandenberg data and is consistent with the technique used in the KSC analyses.

The statistical measures of accuracy are shown in Table 6 which includes the same statistics applied to the Eastern Range: Hit Rate (HR), False Alarm Rate (FAR) and Success Score (SS). Overall the HR was dependent on event type. The FAR overall were poor and had similar values to KSC. The SS for all events were very low with only one event having greater than a 40% success rate.

Criteria	Hit Rate	False Alarm	Success Score
	Probability of Issued Warning meeting desired lead time (ignoring FA)	Ratio	Probability of Issued warning meeting desired lead time (including FA)
<b>Severe Events</b>			
Tornado/Waterspout	0.00		0.00
LTG	0.84	0.67	0.31
Hail Any Size	0.33	0.80	0.14
<b>Precipitation</b>			
Heavy rain (> 2 inches in 12 hours)	1.00	0.60	0.40
<b>Convective Winds</b>			
Winds 35-49 Knots (Convective)	1.00	0.67	0.33
<b>Non-convective Winds</b>			
Winds 35-49 Knots (Non-Convective)	0.68	0.52	0.39
Winds 50-64 Knots (Non-Convective)	0.33	0.88	0.10
Winds GTE 65 Knots (Non-Convective)	0.23	0.75	0.14

\* empty columns due to 0 in denominator

Table 6. Statistical measures of accuracy at Vandenberg AFB or Western Range.

### 5.3.1. Severe Events

Severe events are not as common in southern California due to the maritime westerly influence from the Pacific Ocean. In almost four years, there were only 19 occurrences of lightning and three instances of hail. However, the issued forecasts for these events were twice the number required. This is reflected in the HR, FAR and SS. Table 6 shows that although the HR is high (84%) for lightning, the FAR and SS do not complement these results. The FAR is high (67%) with SS results only around 31%.

Although there were a total of three hail events for the four years, all in the winter season, there were seven forecasts issued, all in the spring. This is reflected in the high FAR (80%) and low SS (14%). There was only one tornado forecast required for the entire four years. It was issued with no lead time or negative lead time, which is shown by the value of 0 for HR and SS.

### **5.3.2. Precipitation**

Precipitation greater than 2 inches/12 hours was the only LCC reported for this time period. Overall, there were only two occurrences (both that met the desired lead time) and three false alarm forecasts. This is reflected in the FAR and SS. However, since there are so few events, it is difficult to analyze their capability.

### **5.3.3. Convective Winds**

Since there were so few severe episodes, it is not surprising that there was only one convective wind case that was required and two false alarms for winds between 35-49 kt. Overall, severe weather including convective winds is not as big a concern as other atmospheric conditions at the Western Range. There were no reported or forecasted wind cases above 50 kts for this study period.

### **5.3.4. Non-Convective Winds**

Unlike the Eastern Range, non-convective winds were the most frequently occurring type of meteorological event at the Western Range. These winds were broken up into three categories, 35-49 kt, 50-64 kt, and greater than 65 kt winds. Winds 35-49 kt had the most occurrences at 257, winds 50-64 kt occurred only 3 times and greater than 65 kts occurred 13 times.

1. At 68%, the HRs for 35-49 kt non-convective winds was greater than the other two non-convective wind types. Stronger winds, 50-64 kt and GTE 65 kts had much lower HRs with 33% and 23% respectively. As can be expected, the FAR showed similar results with the lowest value, 52%, for 35-49 kts and higher values for the stronger winds (88% and 75%). These values show that the majority of forecasts for the stronger winds are false alarms.
2. The success score for 34-49 kt non-convective winds was 39%. For the stronger winds, they were extremely low with success rates only at 10% for 50-64 kt winds and 14% for GTE 65kts. For the stronger winds, there is still room for improvement with the majority of all forecasts being false alarms. This is also reflected in the SS. These strong winds, although infrequent, seem to be the most difficult to forecast.

### **5.3.5. Summary**

Overall the HR was dependent on the event type and the false alarm rates for all events were high. This indicates that the forecasters are forecasting events that do not

verify (overforecasting). The majority of the events had a low SS. SS includes false alarms in its calculation and can be reduced by any tendency to overforecast.

False alarm rates are considerably high in almost all weather events. The exception is 35-49 kt non-convective winds (52%). Even though this is not as large as some of the other values, it still indicates that the state of forecasting is not sufficiently advanced to meet current space launch requirements. Analysis of almost four years of data shows that like the Eastern Range, significant shortfalls exist in our current ability to forecast the following events to the level of specificity required by space launch at the Western Range:

1. Non-Convective Winds
2. Thunderstorms and Associated Hazards (including winds, hail, lightning)
3. Rainfall Rates and Amounts

### 5.3.6. Actual Lead Times for Western Range

Similar to the Eastern Range, in order to determine the frequency that a forecast or weather advisory was successfully issued within the desired lead time, forecast lead times for meteorological events were analyzed. For Vandenberg, only two event types had their lead times tracked from 2002-2004. These are lightning and non-convective winds from 35-49 kts. The desired lead time (DLT) is 30 minutes for lightning and 60 minutes for winds. Histograms showing the number of issued warnings or advisories for each lead time category are shown in Figures 9 and 10.

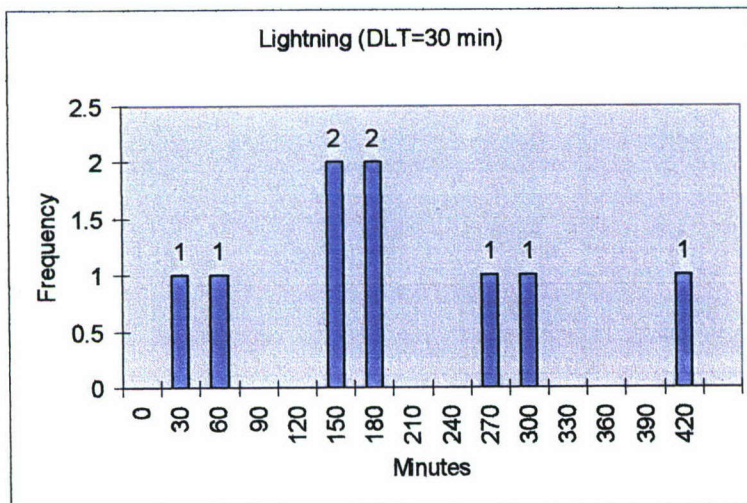


Figure 9. Lightning forecast lead times for Western Range.

Lightning had only 9 recorded warnings/advisories in the two years they were tracked, as distributed by lead time in Figure 5. There was only one lightning event, or 11%, in which the forecast was less than the 30 minute desired lead time. The other

events ranged from 40 minutes to 390 minutes and were all forecasted accurately and within a reasonable time frame.

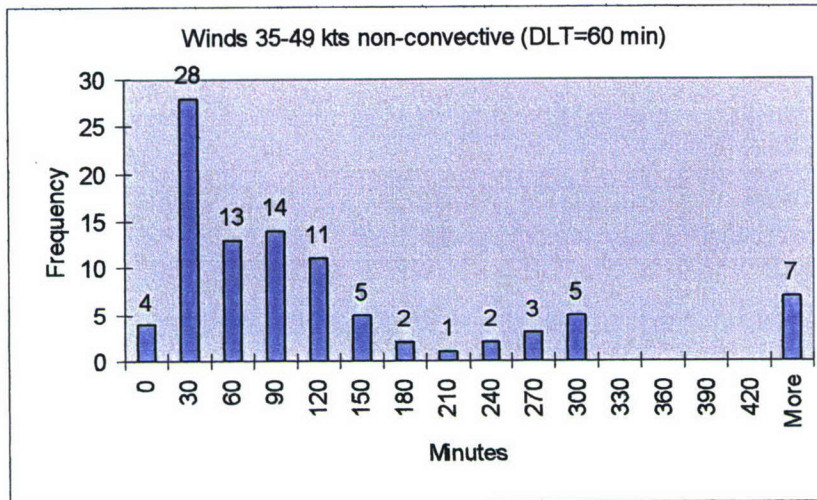


Figure 10. Non-convective winds 35-49 kts forecast lead times for Western Range.

Figure 10 shows the forecast lead times for the non-convective winds. There were 44 forecasts that were less than the 60 minute lead time. The 13 values at the 60 minute column indicate that there were 13 lead times with values from 31 to 60 minutes. Of these 13 lead times, only one is less than the actual DLT, would be considered a missed forecast. This explains the 44 values that were less than the DLT. Values in the 0 column indicate negative or no lead times. For non-convective winds, just under half, or 46%, of the lead times were below the required time. This demonstrates how forecasters were unsuccessful in issuing a forecast on time for about half of their forecasts. This indicates the difficulty of predicting non-convective winds over the launch area more than an hour before their occurrence.

Non-convective winds seem to be the one of the larger concerns for the Western Range. This is apparent during the warmer months where, climatologically, a high pressure zone forms over the Pacific Northwest and a low pressure system forms over Mexico. This strong pressure gradient causes a warm, easterly wind to flow over southern California and is a major contributor to the large number of non-convective wind events. Under certain circumstances, strong non-convective winds develop over the launch site. One condition occurs after a frontal system moves through the area. A strong Great Basin high develops, a leeside trough develops in western California. Also, before a front develops and there is a strong surface low to the southwest of the launch site, in conjunction with a strong high over the southern Rockies, moderate to strong non-convective winds can develop over southern California.

## **6. RESEARCH OPPORTUNITIES AND AFRL AREAS OF MAXIMUM RETURN**

In order to determine the most efficient way to improve weather forecasting in support of space launch, a survey of current research by outside agencies was conducted. This allowed us to propose research which leverages/complements efforts by other organizations. Such research forms our list of AFRL areas of maximum return.

### **6.1. Recent Research in Support of Space Launch**

Our survey of current research indicates that while research is being conducted in the areas of severe weather which includes lightning, waterspouts, tornadoes and convective winds, more research is needed to fully support the unique needs of responsive launch.

Current research in lightning involves work by Mach (1989), Collier (1997), and Johnson and Vaughan (1999). They have all analyzed lightning threats during three shuttle operational phases: rollout, on-pad and launch. Mach states that during rollout and on-pad, there is a possibility of damaging the solid rocket booster and external tank which would cause the greatest damage to the space shuttle. Collier continued this research and also focused on the boost phase of launch, and found that there is a higher risk of both triggered and natural lightning. The latest study by Johnson and Vaughan confirm that more studies are needed to understand triggered lightning. Roeder et al. (1999) state the importance of the distinction between natural and triggered lightning. Ten of the eleven LCC are specified for triggered lightning. Approximately one-third of all space launch countdowns are delayed or scrubbed due to natural or triggered lightning threats or both (Hazen et al. 1995).

Orville (1991, 1994) showed that storms that develop in a southwesterly flow tend to have the highest frequency of cloud-to-ground (CG) lightning in the US. Gremillion and Orville (1999) discussed the likelihood of predicting the onset of CG lightning through signatures indicated by WSR-88D weather radar. They found that the 40-dBZ echo detected at the -10°C temperature height is the best indicator for predicting the onset of CG lightning activity. Wilson and Megenhardt (1997) studied thunderstorm initiation, organization, and lifetime in association with Florida boundary layer convergence. They researched mostly convergence lines developed by east coast seabreeze front and gusts from the west that developed initially from the west seabreeze front. Surprisingly, more thunderstorm systems were associated with the west coast fronts than the east coast. The convergence associated with the east coast fronts tended to be shallower and have weaker updrafts.

Some of the latest research focuses on developing a new global positioning system (GPS) lightning index (Mazany et al., 2002). This is formulated by conducting a statistical analysis of integrated precipitable water vapor data from a GPS receiver located at KSC along with other data collected at the facility. Initial results show the index improved the KSC desired lead time by nearly 10% and has shown significant decreases in false alarms of predicted lightning events.

The following aspects of lightning require further research: the threat of triggered lightning affecting operational launch stages, climatological study of synoptic scale patterns that initiate thunderstorm development over KSC, and better understanding of thunderstorm duration including onset and cessation.

Electrified anvil clouds can enhance the threat of natural and triggered lightning to space launch and landing operations. Many times the associated thunderstorm is not located near the launch site. Research in lightning associated with anvil cirrus has been performed by Short, Wheeler and Lambert all from the Applied Meteorology Unit (AMU) at KSC. Short et al. (2003) studied 49 anvil-case days during the months of May to July 2001. They noted that anvil clouds propagated with the upper-tropospheric winds at altitudes from 9 to 14 km for approximately 2 h. A three-part report by AMU found that an anvil forecast tool did not exist and described the development of such a capability (Lambert, 2000). Short and Wheeler (2002) developed a preliminary tool to predict anvil clouds with lightning potential. Recommendations included adding tropopause pressure, wind profiler data and weather prediction model data every 12 h in order to enhance the effectiveness of the tool. The final phase of this project provided a graphical tool to allow the user to forecast a threat of anvil development over KSC/CCAFS from 3 to 60 h prior to the event (Wheeler and Short, 2003).

Other cloud studies include a short-range forecast guidance of cloud ceilings at KSC (Lambert, 2001). Their analysis determined that more LCC cloud ceiling requirements were violated during the cold season than any other time period. The probability of detection rate was higher than their false alarm rate. However, their best forecast performance was for 1 h lead time forecasts and dropped significantly with increasing lead time. Ward and Merceret (2004) developed an automatic process to determine cloud boundaries using cloud physics and ground-based radar data. It performs an automated analysis of the variation of the electric field and radar reflectivity with distance from the cloud edge. The goal was to be able to use these results to improve the Lightning Launch Commit Criteria weather constraints. Their results show that this algorithm performed slightly better than manual analysis. The results are based on an extensive dataset which they admit was very labor intensive when performed manually. This methodology was developed for specific instrumentation but they suggest that it could be applicable to other types. Certain instrumentation caused larger noise levels than others.

More research is needed in forecast guidance of cloud ceilings and detecting anvil clouds over KSC. Research in detecting anvil separation and threat of electrified anvils appears to be limited to that mentioned above. There has been no reported testing of the anvil detection tool's capability.

Present research in convective winds is broken down into two main areas: peak wind analysis and midtropospheric/upper level winds. Several studies have been performed to try to forecast peak winds at KSC at several launch pads. Storch (1999) compared the forecast method he developed to persistence; however, the method did not show good skill in predicting peak winds. Cloys (2000) conducted a similar study in which the predicted winds were compared to persistence, conditional climatology, and

random forecasts. None of the methods in the analysis performed well enough to be used in operations. Finally, Coleman (2000) developed a conditional climatology of cool season winds at several of the towers at KSC. The results indicated the conditional climatologies did not perform well and were not recommended for use. The AMU conducted two statistical analysis studies of peak winds for the CCAFS. The first study calculated the statistics of peak and average wind speed means and standard deviations (Lambert, 2002). They calculated the probabilities of occurrence of the 5-minute peak and average winds for all towers at the KSC/CCAFS. The goal was to provide a peak wind forecasting tool to use during launches. The results showed that the tool could not capture the physical properties that cause gusts but was able to use the statistics as guidance. The second report presented a recalculation of the wind statistics using a 10-minute peak since these values are used as the standard for verifying wind speed (Lambert, 2003). The results were very similar to the 5-minute peak study.

There has been great difficulty predicting the actual peak wind speed and further research is needed. The majority of the research has been focused on convective winds with limited research on non-convective winds. There are a few papers dedicated to the synoptic flow regime during space shuttle landings (Bauman and Businger, 1996; Bauman et al., 1997), but there is very little information about favorable large-scale patterns for convective activity during launches. While a few papers discuss an analysis of the detailed meteorological dynamics associated with a specific launch, there are very few articles discussing the influence of the large-scale flow and its relation to convective wind strength, direction and climatology of storm type.

A considerable body of research relevant to space launch prediction shortfalls has focused on mesoscale modeling. Case et al. (2002) presented a verification of high-resolution Regional Atmospheric Modeling System (RAMS) forecasts centered over CCAFS. They executed the RAMS model at a grid spacing sufficient to resolve ocean and river breezes as well as convection. The model outperformed a widely used meteorological model, ETA, in most cases. Skill scores for predicting thunderstorm onset were much lower than for predicting seabreeze effects. Case et al. (2001) also used high resolution data to support operational short-range weather forecasting over east-central Florida, including the KSC and CCAFS. The goal was to run this product locally at Spaceflight Meteorology Group (SMG) and the National Weather Service (NWS) Melbourne (MLB), in order to develop a cycling scheme that isolates mesoscale features such as convective outflow boundaries in short-range numerical forecasts

There are no mesoscale modeling forecast studies which incorporate the majority of observational data available at KSC/CCAFS. Most studies utilize either surface observations or data from specific instrumentation. With the large quantity of atmospheric measurements available, more mesoscale modeling research is needed to maximize their use to aid in forecasting.

## **6.2. Potential AFRL Contributions “Areas of Maximum Return”**

Weather phenomena are closely linked to each other. It is impossible to accurately predict lightning and inaccurately predict thunderstorms. Temperatures are related to synoptic scale events as well as to individual cloud locations. Effective research must consider both overall specification and prediction of the state of the atmosphere and prediction of specific phenomena.

## **6.3. Proposed AFRL Research into Specification and Prediction of the State of the Atmosphere**

### **1) Integration and exploitation of weather data**

**Task:** Develop methods to integrate weather data from both local and remote sensors in order to determine the state of the atmosphere. Develop methods to modify weather models to accept data as it becomes available (in real time). Develop methods to modify weather models to accept new sources of data.

**Discussion:** Launch sites are among the most heavily instrumented areas in meteorology. Numerous papers have been written using data gathered in support of space launch. Unfortunately methods have not been developed and implemented to integrate this data into a coherent picture of the state of the atmosphere. Meteorologists spend a great deal of effort taking data from various sources and trying to form a picture of the atmosphere. This is especially difficult at KSC due to the number of different sensors/systems. A single integrated environmental picture would help meteorologists better understand the current state of the atmosphere and better advise launch personnel on potential hazards.

The current state of the atmosphere is the starting point for all numerical weather prediction. If the initial data fields fed into a numerical model are wrong the predictions will not be accurate – regardless of the model. The integration of launch site sensors combined with the integration of remote sensors shows promise to improve prediction of weather over the launch site. Such improvements would form the basis for improved severe weather forecasts, improved wind forecasts and improved cloud and temperature forecasts.

#### **Shortfalls Addressed:**

- Prediction of conditions necessary/sufficient for generation of lightning
- Prediction of severe weather events (thunderstorms, hail, lightning, convective wind)
- Prediction of high winds
- Rainfall rates
- Temperature prediction

#### **Level of Effort:**

- 1 Senior Research Meteorologist/Project Leader
- 1 Research Meteorologist

1 Numerical Weather Prediction Expert  
1 Computer Scientist

Cost: \$850K/yr, 2 years

## 2) Improved modeling of physical phenomena

**Task:** Research improvements in modeling of physical phenomena. Improve current weather models to include physical phenomena related to weather events critical to space launch.

**Discussion:** Accurate prediction of the atmosphere depends on the ability of a weather model to represent physical phenomena. These phenomena (including water cycle, hydrology, cloud processes etc.) are referred to as the model's "physics package." In order to accurately forecast to the level of detail required by space launch significant improvements to the physics package of current operational models need to be developed. We expect that the phenomena of interest should be explicitly predicted rather than parameterized, so the model should be executed at sufficient spatial scales. For example, an increased understanding of in-cloud physical processes and better modeling of turbulent processes is required to determine the position of clouds and the transport of energy through the atmosphere.

### Shortfalls Addressed:

Prediction of conditions necessary/sufficient for generation of lightning  
Prediction of severe weather events (thunderstorms, hail, lightning, convective wind)  
Rainfall rates  
Temperature prediction

### Level of Effort:

1 Senior Research Meteorologist/Project Leader  
1 Numerical Weather Prediction Expert – Physics Package  
1 r Physicist (Thermodynamics), Atmospheric Electricity

Cost: \$635K/yr, 2 years

## **6.4. Proposed AFRL Research into Specific Atmospheric Phenomena**

### 1) Phenomena: Lightning onset and cessation

**Task:** Develop tools to predict the time of onset and cessation of conditions conducive to lightning formation using current data sources.

**Discussion:** Lightning is the top forecast challenge at KSC. Significant effort has gone into observing lightning and there are numerous sources of data. Many studies have been conducted linking lightning onset to atmospheric measurements. One of the biggest challenges is to use the abundance of data/information to develop a tool that allows forecasters to easily determine when lightning will occur and when it will stop

occurring. The development of such a tool would require a thorough review of lightning observation data/measurements and the concurrent atmospheric conditions. The tool would serve to integrate weather data from numerous sources into a specific forecast of the probability and duration of lightning.

**Shortfalls Addressed:**

Prediction of conditions necessary/sufficient for generation of lightning

**Level of Effort:**

.5 Research Meteorologist/Project Leader

.5 Physicist (Thermodynamics), Atmospheric Electricity

Cost: \$210K/yr, 1.5 years

**2) Phenomena: Lightning onset and cessation**

**Task:** Develop new models to measure and forecast atmospheric charge

**Discussion:** Lightning is the top forecast challenge at KSC. Significant effort has gone into observing lightning and there are numerous sources of data. Many studies have been conducted linking lightning onset to atmospheric measurements. The proposed research would seek to model the charged atmosphere in an effort to predict the onset of lightning- causing conditions. This is a long-range project and would have to proceed in phases starting with a feasibility study.

**Shortfalls Addressed:**

Prediction of conditions necessary/sufficient for generation of lightning

**Level of Effort:**

.5 Research Meteorologist/Project Leader

.5 Physicist (Thermodynamics), Atmospheric Electricity

Cost: \$210K/yr, 2 years

**3) Phenomena: Temperature extremes**

**Task:** Develop model output driven temperature curves

**Discussion:** The prediction of temperature extremes is extraordinarily difficult. Often the temperature will change significantly as sky conditions change. For example, if winter skies clear unexpectedly the predicted low temperature can be off by 20 degrees. A tool linking fine scale model output and predicted temperatures will help forecasters accurately predict the onset of cold weather and issue warnings as needed.

Shortfalls Addressed: Temperature prediction

Level of Effort:

.25 Research Meteorologist

.25 Computer Scientist

Cost: \$100K/yr, 1 year

#### 4) Phenomena: Convective precipitation rates

Task: Develop techniques to improve short-term (0-3 h) predictions of rainfall amounts from identified convective cells

Discussion: Prediction performance statistics have shown that there is a significant tendency to predict heavy rainfall events at KSC that don't occur. In an attempt to reduce the number of false alarms of heavy rain events, a real-time or nowcast tool would be developed to assess heavy rainfall potential of organized convection. This tool would draw upon information from weather radar, GPS-derived precipitable water, numerical model predictions, and other relevant information to produce graphical guidance for the forecaster.

Shortfalls addressed: Rainfall rates

Level of Effort:

.5 Research Meteorologist/Project Leader

.5 Meteorologist (Thermodynamics)

Cost: \$210K/yr

## 7. RECOMMENDATIONS

We recommend AFRL fund and execute a research program to improve the quality of weather support to space launch. Space launch is, and will continue to be, significantly more sensitive to weather than the majority of USAF missions. Improvements in weather prediction will lead to significant increases in operational responsiveness and decreased cost. AFRL has a role to play as the Air Force's science laboratory. The program outlined in this paper allows AFRL to leverage efforts conducted elsewhere in the research community while greatly improving the state of science in direct support of USAF space launch. It builds a set of core capabilities (both in specification/prediction of the state of the overall atmosphere and in specific areas) and allows for expansion based on specific customer driven concerns.

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## Appendix A.

### 44<sup>th</sup> Weather Squadron Instrumentation

(Excerpt from "METEOROLOGICAL AND OCEANIC INSTRUMENTATION AT SPACEPORT FLORIDA OPPORTUNITIES FOR COASTAL RESEARCH," Roeder et al.)

#### A1. Local Meteorological and Oceanic Sensors

The 45 WS has a large suite of weather sensors to conduct their weather support mission (Harms et al., 1998). This suite of sensors may be the most dense and most unique in all of operational meteorology. A brief list of these weather systems is provided in Table A1. The geographical distribution of most of the weather sensors is shown in Figure A1. Most of these data are saved and are available for climatological analysis for improved forecasting.

The Florida Institute of Technology also operates some meteorological and oceanographic sensors at two sites about 25 and 35 miles south of Spaceport Florida. These sensors are listed in Table A2 and their positions are shown in Figure A2.

The National Data Buoy Center operates three nearby data buoys and three nearby Coastal-Marine Automated Network (C-MAN) stations. These sensors are listed in Table A3 with locations shown in Figure A2.

Numerous other sensors are also available (Case et al., 2002). These include traditional weather sensors like the Automated Surface Observation Site at the Melbourne Airport and non-traditional sensors like the Aircraft Communications Addressing and Reporting System (ACARS) and a GPS Precipitable Water sensor at Cape Canaveral. In addition, a surprising amount of non-traditional data from private industry also exists.

SENSOR	NO	COMMENTS
BOUNDARY LAYER		
Weather Towers	44	30 x 40 Km Area, 2 to 150 m, Wind, Temperature, Humidity
915 MHz DRWP/RAS S	5	Wind (0.12-3 Km), 5 Min Virtual Temperature (0.12-2.5 Km), 15 Min
Mini-Sodars (Projected 2005)	8	Wind (15m-150 m, every 5 m), 1 min

Surface Observer	2	KSC, Patrick AFB (contractor)
Rain Gauges	33	Most collocated at field mill sites (see LPLWS)
<b>UPPER AIR</b>		
Automated Meteo. Profiling System (AMPS) (Low-Res)	1	GPS-tracked RAOB (asynoptic times)
Automated Meteo. Profiling System (High-Resolution)	1	GPS-tracked Jimsphere (High precision wind balloon, countdowns only)
Rocketsonde (Not After 2000)	1	20-90 Km, Limited launches
50 MHz DRWP	1	Winds (2.0-19.0 Km), 112 Gates (150 m spacing), 5 Min refresh rate
<b>LIGHTNING</b>		
Lightning Detection And Ranging (LDAR)	7	Detects all lightning types, Depicts 3-D structure
Launch Pad Lightning Warning System (LPLWS)	31	Surface electric field, Detects all lightning types (poor location accuracy)
Cloud to Ground Lightning Surveillance	6	Improved Accuracy with Combined Technology

System (CGLSS)		(IMPACT) sensors
NLDN *	105	Commercial data source
A. D. Little	1	Detects all lightning types in range bins
RADAR		
WSR-74C/IRIS	1	5 cm, 2.5 Min Volume Scan, Customized Products
WSR-88D *	1	NWS/Melbourne

\* Not a local weather sensor, but is included for its importance in operational research or for completeness.

Table A1. List of local weather sensors used by 45 WS. Most of these data are saved and are available for after-the-fact study.

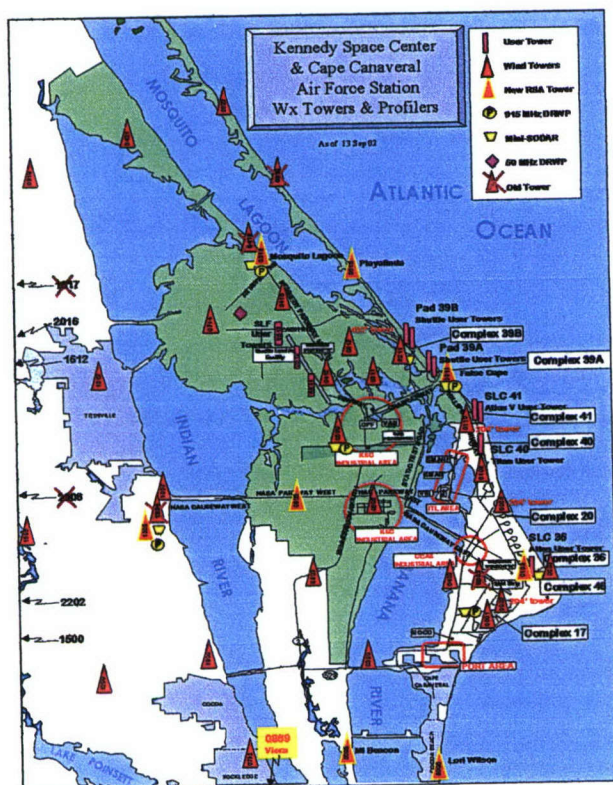


Figure A1. Locations of most of 45 WS weather sensors

SENSOR	NO.	COMMENTS
<b>SEBASTIAN INLET NORTH JETTY</b> (27.86 N, 80.45 W)		
Automated Weather Station	1	Temperature, Dew Point, Wind, Surface Pressure
Tide Gauge	1	None
Wave Gauge	1	Directional spectrum
<b>FLORIDA INSTITUTE OF TECHNOLOGY (28.07 N, 80.16W)</b>		
GPS Precipitable Water	1	Precipitable Water, Surface Pressure, Temperature, Relative Humidity
Wind Station	1	Winds
Research devices from which related weather data can be inferred	Variable	E.g., Solar Panels, Irradiance Meter, Wind Turbines, etc.

Table A2. List of weather and oceanographic sensors used by the Florida Institute of Technology. Most of these data operate continuously, are routinely saved and are available for after the fact study.

New sensors are also being planned for Florida. For example, the Florida Department of Transportation is installing a network of about 50 GPS-Precipitable Water sensors across Florida.

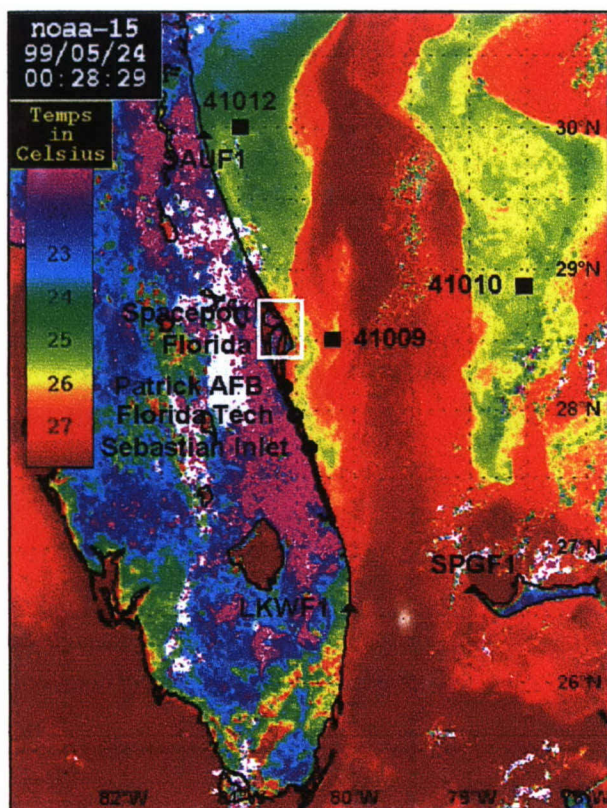


Figure A2. Locations of the nearby meteorological and oceanographic sensors used by the Florida Institute of Technology and the National Data Buoy Sensors

SENSOR	LOCATI ON	COMMENTS
BUOYS		
Station 41009 Canaveral	28.50 N, 80.18 W	Air Temperature , Anemometer , Barometer, Sea Temperature
Station 41010 Canaveral East	28.89 N, 78.52 W	Same As Above
Station 41012	30.00 N, 80.50 W	Same As Above

St. Augustine		
C-MAN STATIONS		
Station SAUF1 St. Augustine, FL	29.86 N, 81.26 W	Air Temperature , Anemometer , Barometer
Station LKWF1 Lake Worth, FL	26.61 N, 80.03 W	Same As Above
Station SPGF1 Settlement Point, Grand Bahamas Island	26.70 N, 79.00 W	Same As above
Site specific details available at <a href="http://www.ndbc.noaa.gov">www.ndbc.noaa.gov</a>		

Table A3. List of nearby weather and oceanographic sensors from the National Data Buoy Center.

**Appendix B.  
Launch Commit Criteria**

Platform	Type	Criteria	Lead Time	Reference
<b>LIGHTNING</b>				
KSC	warning	Lightning w/i 5 nm of any area	0	Boyd. B, 1995
KSC	advisory	Lightning w/i 5 nm of any area	30 min	Boyd. B, 1995
KSC	advisory	Lightning w/i 5 nm of any area	30 min	Boyd. B, 1995
Shuttle	no launch	Lightning detected within 10 nm of pad or flight path within 30 min to launch		Diller, 2003
Shuttle	no launch	Lightning obs. And cloud within 10 nm of flight path		Diller, 2003
Atlas 5	no launch	Lightning w/i 5 nm of any Complex 41 while on pad		www.spaceflightnow.com Jim Sardonia, 45 WS Aug 2002
Shuttle	no tanking	forec. > 20% lightning within 5 nm of launch pad during first hour of tanking		Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	lightning in tstorm within 10 nm of flight path for 30 min		www.spaceflightnow.com Jim Sardonia, 45 WS
<b>ELECTRIC FIELD MILL</b>				
Shuttle	no launch	1 min avg of electric field mill network not exceed -1 or +1 kv/m within 5 nm of pad or lightning flash 15 min to launch		Diller, 2003
<b>Thunderstorm (GENERAL)</b>				
KSC	advisory	Tstorm within 25 nm of RCC	1 hr	Boyd. B, 1995
Shuttle	no launch	if flight path thru tstorm debris cloud, non-transparent and < 3 hrs old		Diller, 2003
<b>Tornado/Waterspout</b>				
KSC	warning	Tornado	5 min	Boyd. B, 1995

CCAFS	warning	Tornado	5 min	Boyd. B, 1995
KSC	warning	Waterspout	5 min	Boyd. B, 1995
CCAFS	warning	Waterspout	5 min	Boyd. B, 1995
KSC	advisory	Waterspout/Funnel Cloud	5 min	Boyd. B, 1995
<b>HAIL</b>				
CCAFS	warning	Hail $\geq 3/4"$	30 min	Boyd. B, 1995
KSC	warning	Hail (any size)	30 min	Boyd. B, 1995
<b>ANVIL CLOUD (ATTACHED)</b>				
Shuttle	no launch	Thru attached anvil cloud		Diller, 2003
Shuttle	no launch	Within 10 nm of a cloud or anvil producing lightning for 30 min after last lightning		Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path thru non-transparent attached anvil		www.spaceflightnow.com Jim Sardonia, 45 WS
Atlas 2A, 2AS, 5 Delta 4	no launch	within 5 nm of non-transparent attached anvil for first 3 hrs after last lightning		www.spaceflightnow.com Jim Sardonia, 45 WS
Atlas 2A, 2AS, 5 Delta 4	no launch	within 10 nm non-transparent parts of attached anvil for 30 min after last lightning		www.spaceflightnow.com Jim Sardonia, 45 WS
<b>ANVIL CLOUD (DETACHED)</b>				
Shuttle	no launch	if flight path is thru non-transparent parts of detached anvil for 3 hrs after detachment		Diller, 2003
Shuttle	no launch	if flight path is within 10 nm of non-transparent detached anvil for 30 min after lightning in anvil or parent cloud		Diller, 2003
Shuttle	no launch	if flight path within 5 nm of non-transparent parts of detached anvil for 3 hrs after lightning in parent or anvil cloud		Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	thru detached anvil for first 3 hrs after detachment		www.spaceflightnow.com Jim Sardonia, 45 WS

Atlas 2A, 2AS, 5 Delta 4	no launch	thru non-transparent detached anvil for first 3 hrs after last lightning	www.spaceflightnow. com Jim Sardonia, 45 WS
Atlas 2A, 2AS, 5 Delta 4	no launch	within 5 nm of non-transparent detached anvil for first 3 hrs after last lightning	www.spaceflightnow. com Jim Sardonia, 45 WS
Atlas 2A, 2AS, 5 Delta 4	no launch	within 10 nm non-transparent parts of detached anvil for 30 min after last lightning	www.spaceflightnow. com Jim Sardonia, 45 WS

#### PRECIPITATION

KSC	advisory	>= 1' precip in <= 1 hr	30 min	Boyd. B, 1995
Shuttle	no launch	no precip at launch pad or flight path		Diller, 2003

#### WINDS

KSC	advisory	Wind Sfc-300' >= 17 kts	30 min	
KSC	warning	Wind Sfc-300' >=35 kts	30 min	Boyd. B, 1995
KSC	warning	Wind Sfc-300' >=50 kts	30 min	Boyd. B, 1995
KSC	warning	Wind Sfc-300' >=60 kts	30 min	Boyd. B, 1995
CCAFS	warning	Wind Sfc-200' >=35 kts < 50 kts	60 min	Boyd. B, 1995
CCAFS	warning	Wind Sfc-200' >=50 kts	30 min	Boyd. B, 1995
Shuttle	advisory	Wind in solid rocket booster area > 26 kts		Diller, 2003
Shuttle	no tanking	Wind > 30 kts		Diller, 2003
Atlas 2A	tower rollback	Winds > 30 kts		www.spaceflightnow. com Jim Sardonia, 45 WS Dec 2002
Atlas 2A	tanking in tower	Winds > 40 kts		www.spaceflightnow. com Jim Sardonia, 45 WS Dec 2002
Atlas 2A	no launch	Winds > 27 kts		www.spaceflightnow. com

			Jim Sardonia, 45 WS Dec 2002
Atlas 2AS	tower rollback/ return	Winds > 30 kts	www.spaceflightnow. com Jim Sardonia, 45 WS Sep 2002
Atlas 2AS	no launch	Winds > 29 kts	www.spaceflightnow. com Jim Sardonia, 45 WS Sep 2002
Atlas 2AS	no launch	Winds > 26 kts if from 330-060 deg	www.spaceflightnow. com Jim Sardonia, 45 WS Sep 2002
Atlas 5	platform rollout and return	Winds > 32 kts	www.spaceflightnow. com Jim Sardonia, 45 WS Aug 2002
Atlas 5	no tanking	Winds > 35 kts	www.spaceflightnow. com Jim Sardonia, 45 WS Aug 2002
Atlas 5	no cryo tanking/det ank	Winds > 41 kts	www.spaceflightnow. com Jim Sardonia, 45 WS Aug 2002
Delta 4	rollback	as low as 22 kts measured at 102 ft	www.spaceflightnow. com Jim Sardonia, 45 WS Nov 2002
Delta 4	rollback	as high as 39 kts measured at 102 ft	www.spaceflightnow. com Jim Sardonia, 45 WS Nov 2002
Delta 4	fueling/ vehicle exposure	as high as 25 kts measured at 102 ft	www.spaceflightnow. com Jim Sardonia, 45 WS Nov 2002
Delta 4	no launch	18 kts meas. 102 ft (from 262-042 deg)	www.spaceflightnow. com Jim Sardonia, 45 WS Nov 2002
Delta 4	no launch	18 kts meas. 102 ft (from 042-087 deg)	www.spaceflightnow. com Jim Sardonia, 45 WS

			Nov 2002
Delta 4	no launch	18 kts meas. 102 ft (from 087-197 deg)	www.spaceflightnow.com Jim Sardonia, 45 WS Nov 2002
Delta 4	no launch	18 kts meas. 102 ft (from 197-262 deg)	www.spaceflightnow.com Jim Sardonia, 45 WS Nov 2002
<b>Temperature</b>			
KSC	advisory	Temp <= 40F for >= 2 hrs	4 hr Boyd. B, 1995
KSC	advisory	Temp <= 32F for >= 2 hrs	16 hr Boyd. B, 1995
KSC	advisory	Temp <= 25F for >= 2 hrs	4 hr Boyd. B, 1995
Shuttle	no tanking	24 hr avg temp < 41F	Diller, 2003
Shuttle	no countdown	Temp > 99F for > 30 min	Diller, 2003
Shuttle	no countdown	Temp < min for > 30 min	Diller, 2003
Atlas 2A	no launch	Temp < 40 F	www.spaceflightnow.com Jim Sardonia, 45 WS Dec 2002
Atlas 2AS	no launch	Temp < 40 F	www.spaceflightnow.com Jim Sardonia, 45 WS Sep 2002
<b>Cloud Temperature</b>			
Shuttle	no launch	Clouds w/ tops < 41F level not assoc. tstorm	Diller, 2003
Shuttle	no launch	cumulus clouds w/ tops higher than 41F level	Diller, 2003
Shuttle	no launch	Thru non-transparent clouds that extend to or above 32F level that are assoc. inclement weather within 5 nm	Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path within 10 nm of cumulus top higher than -20 C level	www.spaceflightnow.com Jim Sardonia, 45 WS

Atlas 2A, 2AS, 5 Delta 4	no launch	flight path within 5 nm of cumulus top higher than -10 C level	www.spaceflightnow. com Jim Sardonia, 45 WS
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path thru cumulus top higher than -5 C level	www.spaceflightnow. com Jim Sardonia, 45 WS
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path thru cumulus top between +5 and -5C levels	www.spaceflightnow. com Jim Sardonia, 45 WS

#### **Cloud Thickness**

Shuttle	no launch	flight path thru layer of clouds within 5 nm that $\geq$ 4500 ft thick and temp of layer is between 32F and -4F	Diller, 2003
Shuttle	no launch	for 4000-6000 ft, cloud thickness < 500 ft, veh. Integrity obs thru 8000ft, instrum. Functioning, 45 WS approves	Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path thru non-transparent cloud layer > 4500ft thick between 0C and - 20C level	www.spaceflightnow. com Jim Sardonia, 45 WS

#### **Cumulus Cloud**

Shuttle	no launch	Thru nearest edge of cumulus type clouds w/ tops higher than 14F level	Diller, 2003
Shuttle	no launch	Thru or within 10 nm of nearest edge of cumulus with tops higher than -4F level	Diller, 2003
Shuttle	no launch	if flight path thru cumulus cloud developed from smoke plume for 60 min after detachment	Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	within 5 nm flight path thru non- transparent clouds assoc. w/ weather disturbance w/ clouds above 0C level contain moderate precip (or melting)	www.spaceflightnow. com Jim Sardonia, 45 WS

Atlas 2A, 2AS, 5 Delta 4	no launch	non-transparent cloud is connected to above cloud layer unless no evidence containing liquid water or located entirely at temps of -15C or colder	www.spaceflightnow.com Jim Sardonia, 45 WS
<b>Visibility</b>			
Shuttle	no launch	for 6000-8000ft, no launch if veh. integrity obs. thru 6000ft, instrum. functioning, 45 WS approves	Diller, 2003
Shuttle	no launch	if no direct visual obs of shuttle thru 8000 ft	Diller, 2003
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path thru non-transparent parts of debris clouds for 3 hrs	www.spaceflightnow.com Jim Sardonia, 45 WS
<b>SOLAR RADIATION</b>			
Atlas 2A	no launch	solar radiation: 50 MeV Proton Flex not greater than 100 pfu	www.spaceflightnow.com Jim Sardonia, 45 WS Dec 2002
Atlas 2AS	no launch	solar radiation: 50 MeV Proton Flex not greater than 100 pfu	www.spaceflightnow.com Jim Sardonia, 45 WS Sep 2002
<b>Misc.</b>			
Atlas 2A, 2AS, 5 Delta 4	no launch	flight path thru cumulus cloud developed from smoke plume for 60 min after cumulus has detached	www.spaceflightnow.com Jim Sardonia, 45 WS
<b>Flight Rules (EMERGENCY LANDING) and KSC End of Mission Rules</b>			
<b>VISIBILITY</b>			
Microwave Landing System (MLS) capability and weather reconn. Aircraft for Emergency Landing	RTLS	cloud coverage 4/8 or less below 5000 ft and visibility of $\geq 4$ sm	Diller, 2003

Microwave Landing System (MLS) capability and weather reconn. Aircraft for Emergency Landing	AOA, PLS	cloud coverage 4/8 or less below 8000 ft and visibility of $\geq 5$ sm		Diller, 2003
Microwave Landing System (MLS) capability and weather reconn. Aircraft for Emergency Landing	TAL	cloud coverage 4/8 or less below 5000 ft and visibility of $\geq 5$ sm		Diller, 2003
no MLS capability/Emergency Landing	landing hard surface runway	ceiling not $\leq 10,000$ ft and vis. $> 7$ sm		Diller, 2003
KSC End of Mission Landing Weather Flight Rules	no landing	4/8 or less cloud coverage below 8000 ft and visibility $\geq 5$ mi	70-90 min	Diller, 2003
<b>Thunderstorm (GENERAL)</b>				
all for Emergency Landing	RTLS, TAL	no tstorms, lightning, precip. within 20 nm of runway or 10 nm final approach out to 30 nm		Diller, 2003
all for Emergency Landing	RTLS, TAL	no detached opaque tstorm anvil $< 3$ hrs old within 15 nm runway or 5 nm approach out to 30 nm		Diller, 2003
all for Emergency Landing	AOA, PLS	no tstorms, lightning, precip. within 30 nm of runway or 20 nm final approach out to 30 nm		Diller, 2003

all for Emergency Landing	AOA, PLS	no detached opaque tstorm anvil < 3 hrs old within 20 nm runway or 10 nm approach out to 30 nm		Diller, 2003
KSC End of Mission Landing Weather Flight Rules	no landing	no tstorm, lightning, precip within 30 nm facility	70-90 min	Diller, 2003
KSC End of Mission Landing Weather Flight Rules	no landing	detached opaque tstorm anvil < 3 hrs old not within 20 nm facility or 10 nm flight path when orbiter is within 30 nm runway	70-90 min	Diller, 2003
PRECIPITATION				
all for Emergency Landing	RTLS	exception for light precip within 20 nm if tops of clouds < 41F and < 14F in 2.5 hr prior to launch, radar reflectivity < 30 dBZ		Diller, 2003
all for Emergency Landing	TAL	exception for rain showers if < 10 % area within 20 nm, no convective development, top of precip clouds not< 41F and not <14F within 2.5 hrs launch		Diller, 2003
WINDS				
all for Emergency Landing	RTLS, TAL, AOA, PLS	crosswind component not to exceed 15 kts		Diller, 2003
all for Emergency Landing	RTLS, TAL, AOA, PLS	Headwind not greater than 25 kts		Diller, 2003
all for Emergency Landing	RTLS, TAL, AOA, PLS	Tailwind not to exceed 10 kts average, 15 kts peak		Diller, 2003
all for Emergency Landing	RTLS, TAL, AOA, PLS	Turbulence conditions <= moderate intensity		Diller, 2003
KSC End of Mission Landing Weather Flight Rules	no landing	peak cross wind cannot exceed 15 kts, 12 kts at night, mission > 20 days, 12 kts day or night	70-90 min	Diller, 2003

KSC End of Mission Landing Weather Flight Rules	no landing	headwind cannot exceed 25 kts	70-90 min	Diller, 2003
KSC End of Mission Landing Weather Flight Rules	no landing	tailwind cannot exceed 10 kts avg, 15 kts peak	70-90 min	Diller, 2003
<b>Misc.</b>				
KSC End of Mission Landing Weather Flight Rules	no landing	Turbulence conditions <= moderate intensity	70-90 min	Diller, 2003
KSC End of Mission Landing Weather Flight Rules	no landing	consideration for "no go/go" forecast if weather improving	70-90 min	Diller, 2003

Table B1. Launch Commit Criteria for USAF and NASA

## Appendix C.

### Summary of AFSPC Provided Metrics - Eastern Range

Table C1. Summary of AFSPC metrics for Eastern Range

Weather Warning/Advisory Data											
Event	Min criteria	Max criteria	Desired lead time	Required	Issued	DLT	Met	DLT	Met	Met	Neg or False Zero alarms LT
AFSPC Criteria											
Tornado/Waterspout	0	999	>=5	7	19	5	2	0	0	2	12
Fair Weather Waterspout (Advisory)	0	5	>=5	4	8	0	4	0	1	3	4
Winds GTE 60 Knots (Convective)	60	999	>=60	0	1	0	0	0	0	0	1
Winds 50-59 Knots (Convective)	60	999	>=60	18	65	6	12	6	5	1	47
Winds >=50 Knots (Convective)	50	999	>=60	25	109	8	17	9	5	3	84
Winds 35-49 Knots (Convective)	35	49	>=30	322	778	241	81	32	25	24	456
Winds 25-34 Knots (Convective Advisory)	25	34	>=30	146	304	99	47	14	21	12	158
Winds GTE 60 Knots (Non- Convective)	60	999	>=60	0	1	0	0	0	0	0	1
Winds 50-59 Knots (Non-Convective)	60	999	>=60	0	2	0	0	0	0	0	2
Winds >=50 Knots (Non-Convective)	50	999	>=60	2	14	0	2	2	0	0	12
Winds 35-49 Knots (Non-Convective)	35	49	>=30	75	116	53	22	6	9	7	41
Winds 25-34 Knots (Non-Convective Advisory)	25	34	>=30	160	293	126	34	8	13	13	133
Hail Any Size	0	999	>=60	21	92	9	12	7	5	0	71
Heavy rain (≥ 2 inches in 12 hours)	2	999	>=5	8	20	8	0	0	0	0	12
Rain >=1 Inch (Advisory)	1	999	>=30	25	53	17	8	2	4	2	28
LTG	0	5	>=30	3665	6098	2470	1195	815	286	94	2433
Freezing Precip (Advisory)	0	999	>=30	0	0	0	0	0	0	0	0
Temp 32-39F (Advisory)	32	39	>=240	53	75	33	20	9	9	2	22
Temperature 25- 31F (Advisory)	25	31	>=960	26	48	11	15	12	1	2	22
Temperature <=24F (Advisory)	-999	24	>=1440	0	3	0	0	0	0	0	3
Steady Wind >=22 Knots (Advisory)	22	999	>=30	37	58	23	14	6	2	6	21

## Summary of AFSPC Provided Metrics - Western Range

Event	Min criteria	Max criteria	Desired lead time	Required	Issued	Met DLT	Met 50-99%	Met 1-49%	Neg or Zero LT	False alarms
AFSPC Criteria										
Tornado/Waterspout	0	999	>=5	1	1	0	0	0	1	0
Winds 35-49 Knots (Non-Convective)	35	49	>=30/60	257	444	174	26	42	15	187
Winds 50-64 Knots (Non-Convective)	50	64	>=120	3	10	1	0	1	1	7
Winds GTE 65 Knots (Non-Convective)	65	999	>=120	13	22	3	4	5	1	9
Winds 35-49 Knots (Convective)	35	49	>=30/60	1	3	1	0	0	0	2
Winds 50-64 Knots (Convective)	50	64	>=120	0	0	0	0	0	0	0
Winds GTE 65 Knots (Convective)	65	999	>=120	0	0	0	0	0	0	0
LTG	0	5	>=30	19	51	16	2	1	0	32
Hail Any Size	0	999	>=60	3	7	1	0	1	1	4
Heavy rain (≥ 2 inches in 12 hours)	2	999	>=5/30/60	2	5	2	0	0	0	3

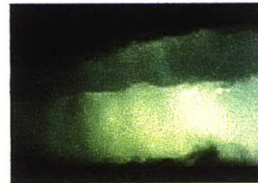
Table C2. Summary of AFSPC metrics for Western Range

**Appendix D.**  
**45<sup>th</sup> Weather Squadron Research Requirements (Adapted from 45<sup>th</sup> Weather Squadron Briefing to Air Force Weather 2004 R&D Summit)**



***OPERATIONAL RESEARCH  
REQUIREMENTS***

- 1) Nowcasting Lightning Cessation**
- 2) Nowcasting Lightning Onset**
- 3) Forecasting Convective Winds**
- 4) Forecasting Elevated Point Peak Winds**
- 5) Tools For Daily 24-Hour And Weekly Planning Forecast**
- 6) Fine-Tune Local Numerical Weather Model**
- 7) Improved Lightning Launch Commit Criteria**
- 8) Data Visualization**
- 9) Applications Of Statistical Process Control**



OPR: 45WS/SYR (pg. 1)

Figure D1. 45<sup>th</sup> WS Operational Research Requirements

**Appendix E. (disk available upon request).**

**RTOMI S0018.100 Adverse Environmental and Lightning Monitoring at LC 39  
NASA Acronym List**

## Appendix F.

### Seasonal Statistical Analysis of Eastern Range by Meteorological Event

Criteria	Hit Rate Probability of issued warning meeting desired lead time (ignoring FA)				False Alarm Ratio				Success Score Probability of issued warning meeting desired lead time (including FA)			
	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Severe events												
Tornado/Waterspout			0.80	0.50	1.00	1.00	0.56	0.80	0.00	0.00	0.40	0.17
F W Waterspout(Adv)					1.00		1.00	1.00	0.00		0.00	0.00
LTG	0.73	0.68	0.69	0.59	0.47	0.52	0.43	0.65	0.44	0.39	0.46	0.28
Hail Any Size		0.33	0.44		1.00	0.95	0.84	1.00	0.00	0.05	0.14	0.00
Precipitation												
Heavy rain (> 2 in/12 h)	1.00	1.00	1.00	1.00	0.67	0.33	0.83	0.50	0.33	0.67	0.17	0.50
Rain >=1 Inch (Adv)	0.67	0.67	0.75	0.33	0.33	0.67	0.65	0.50	0.50	0.29	0.32	0.25
Freezing Precip (Adv)												
Winds Convective							1.00				0.00	
Winds GTE 60 (Conv)		0.33	0.40	0.20	1.00	0.91	0.88	0.75	0.00	0.08	0.11	0.13
Winds 50-59 (Conv)		0.40	0.38	0.14	1.00	0.91	0.91	0.88	0.00	0.08	0.08	0.07
Winds GTE 50 (Conv)	0.65	0.71	0.77	0.75	0.82	0.70	0.65	0.53	0.16	0.27	0.32	0.41
Winds 35-49 (Conv)	0.55	0.63	0.65	0.64	0.73	0.60	0.64	0.55	0.22	0.37	0.30	0.36
Winds 25-34(Conv Ad)												
Winds non convective							1.00				0.00	
Winds GTE 60(NonConv)					1.00			1.00	0.00			0.00
Winds 50-59(NonConv)					1.00		1.00	1.00	0.00		0.00	0.00
Winds GTE 50(NonConv)							1.00	1.00	0.39	0.44	0.00	0.57
Winds 35-49(NonConv)	0.67	0.64	0.00	0.81	0.51	0.42	1.00	0.34	0.45	0.47	0.36	0.37
Winds 25-34(NonConvAd)	0.86	0.85	0.67	0.66	0.51	0.49	0.56	0.54	0.18	0.42	0.00	0.90
Steady Wind >=22 (Adv)	0.33	0.69		0.90	0.73	0.48	1.00	0.00				
Temperature												
Temp 32-39F (Adv)	0.64	0.50			0.33	0.83		1.00	0.48	0.14		0.00
Temp 25-31F (Adv)	0.38	1.00			0.64	0.75			0.23	0.25		
Temp <=24F (Adv)					1.00				0.00			
* empty columns due to 0 in denominator												
Definition of Statistics	<b>Probability (hit rate)=</b> $\text{hits}/(\text{hits}+\text{misses})$ Range 0-1. Perfect Score 1  Sensitive to hits but ignores false alarms Very sensitive to climatological frequency of events. Good for rare events *Can be artificially improved by issuing more "yes" forecasts to increase the number of hits (use with FAR)				<b>False Alarm Ratio=</b> $\text{FA}/(\text{FA}+\text{hits})$ Range 0-1. Perfect Score 0  Sensitive to false alarms, but ignores misses. *Can be artificially improved by issuing fewer "yes" forecasts to reduce the number of false alarms. Not often reported for deterministic forecasts.				<b>Success Score=</b> $\text{hits}/(\text{hits}+\text{misses}+\text{FA})$ Range 0-1. 0 is no skill. Perfect Score 1  Measures the fraction of observed and/or forecast events that were correctly predicted "Accuracy when correct negatives have been removed". TS only concerned with forecasts that count.			

Table F1. Seasonal Statistical results for Hit Rate (HR), False Alarm Ratio (FAR) and Success Score (SS)

These events were broken down by season (DJF, MAM, JJA, SON) for comparison. This was only performed on the Eastern Range statistics. There were not enough data at the Western Range to produce statistically significant seasonal statistics.

#### Severe Events

- Lightning forecasts have at least a 68% hit rate in all seasons with the exception of fall (59%). For all lightning forecasts issued, about 40% are false alarms. The false alarm rate is lowest in the summer during the peak of convective activity. The number of successful forecasts averages around 40%.
- Hail events were poorly predicted with 43% of all forecasts meeting the desired lead-time for spring and summer. False alarm rates were extremely high. This is reflected in the low number of successful forecasts ranging from 5-14%. Hail events, although not as common as lightning, are forecast poorly and have an unusually high false alarm rate (95% of all forecasts in the spring and 84% in the summer).

3. Again, the capability to predict severe weather needs improvement to meet current requirements. The data show a lack of confidence in the current state of forecasting as evidenced by high false alarm rates and low success scores.

## **Precipitation**

Our analysis of current capability to forecast precipitation in support of space launch is as follows:

1. Although all heavy rain events were forecast, more than half of the forecasts issued for winter, summer and fall were false alarms. This is especially evident in the summer season where 83% of all forecasts were unnecessarily issued. The success rates or the probability of issued warnings meeting the desired lead-time ranged from 17% in the summer to 67% in the spring. Only in the spring were forecasts correctly issued more than half of the time.
2. Rain events occurred three times more often than heavy rain events. They were successfully forecast more than two-thirds of the time during the winter, spring, and summer seasons. However, the false alarm ratio was very high, with two-thirds of all forecasts unnecessarily issued in the spring and summer.
3. There is significant room for improvement in the forecasting of rain rates/amounts in support of space launch.

## **Convective Winds**

Our analysis of current capability to forecast convective winds in support of space launch is as follows:

1. The SS is very low for all convective wind types. The highest probability of an issued warning meeting the desired lead-time is 41% for winds 35-49 kts during the fall season.
2. Strong convective winds (GTE 50 kts) are poorly forecast with a false alarm rate of 88% or higher. The false alarm rate for convective winds overall is higher than for any other meteorological event. There is a need to improve forecasting of convective winds.

## **Non-Convective Winds**

Our analysis of current capability to forecast non-convective winds in support of space launch is as follows:

1. The HRs for non-convective winds were the highest of any events in the dataset. There was only one season, winter, in which the HR was below 50% (33% for steady winds). For all other seasons and wind events, the HR ranged from 66% to 86%. The FAR was 34% to 56% for most categories (the exception being forecasts of steady winds in the fall season (73%).

2. The success rates for non-convective winds range from 36% in the summer to just 57% in the fall. Although non-convective winds are better forecasted than convective wind events, there is still room for improvement with almost half of all forecasts being false alarms.

## **Temperature**

Our analysis of current capability to forecast temperature thresholds in support of space launch is as follows:

1. The winter HR for 25-31°F is 38% and 64% for 32-39°F. The spring season has a perfect HR for 25-31F, but only half of the forecasts of 32-39F were correct. The FARs are very high (64-83%) for both winter and spring (with the exception of 33% for temperatures ranging from 32-39°F in the winter). The SS are low for both winter and spring.
2. There is room for improvement in the forecasting of temperatures in support of space launch.